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The Relation of Wall Construction to Moisture Accumulation in Fill-Type Insulation

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SUMMARY

The investigation reported herewith was confined to a consideration of factors which enter into the problem of moisture accumulation in insulated and uninsulated walls, with particular reference to fill-type insulation. Both analytical and experimental methods were employed.

In the analytical study, the relation which must exist among the principal factors when no moisture accumulation takes place was evaluated. The results of the study show that the water permeability of the cold side of the wall must be many times that of the warm side to avoid moisture accumulation, even under ordinary conditions.

Water vapor permeability determinations of a number of materials used in wall construction were made. Different methods of measurement of permeability were used to check determinations and to make measurements simulating conditions under which building materials are used. Materials of high permeability are rosin sheathing paper and fiber insulation boards which are not vapor proofed. Those of low permeability are heavy asphalt saturated felts and sisalkraft papers. Aluminum paint, when applied in two coats, serves as a good vapor seal. Other building materials, including plaster, wood and concrete, are permeable to water vapor.

Thirty-three test walls, including frame, brick veneer, double tile and concrete L-block walls, were constructed and subjected to controlled conditions of temperature and humidity. Uninsulated as well as insulated walls were included. A number of the walls were constructed to give wide variation in the water vapor permeability properties of both the warm and cold sides of the wall, for the purpose of observing the effect of these properties on moisture accumulation.

A constant temperature-humidity room was constructed to control the conditions on the warm side of the walls, and mechanical refrigeration was used to maintain low temperatures on the cold side. The conditions maintained were 75°F. and 50 percent relative humidity on the warm side and a temperature of 12 to 16°F. and a relative humidity of 80 percent on the cold side. The period of test for different walls varied from 25 to 72 days. At the end of the test period, moisture samples of the insulation were taken, and the inside of the cold side of the wall

inspected for free moisture. The frame walls were weighed at intervals throughout the test to observe the rate of moisture accumulation.

In general, the results of the tests on the wall sections also show that to prevent accumulation the permeability of the cold side of the wall must be many times that of the warm side. A water vapor barrier in the form of two coats of aluminum paint on the inside surface of the wall reduced the rate of accumulation but did not eliminate it. A similar result was obtained with a wall which had a cold wall of high permeability. Uninsulated walls accumulated moisture as well as insulated walls. The accumulated moisture was always found on the inside of the cold wall.

The Relation of Wall Construction to Moisture Accumulation in Fill-Type Insulation[1]

BY HENRY J. BARRE[2]

Moisture accumulation in building walls through condensation occurs frequently in cold weather, when a high degree of humidification within heated buildings is brought about either artificially or through normal means. The problem is not new and has been apparent in buildings where high humidities exist, as in laundries, livestock structures and creameries. However, in recent years the problem has also been observed in some homes, especially those which are more tightly constructed or in which artificial humidification is practiced to obtain greater comfort. The use of insulation in walls, roofs and attics has, in some instances, aggravated the problem where certain precautions were not taken. The accumulation occurs usually under the roof in the form of frost or on the inside surface of the cold wall during extended periods of cold weather. During warm weather the frost will melt and run down the inside of the walls, resulting in decay hazards and often in redecorating costs.

The purpose of this investigation was to determine the relation of the thermal and water vapor permeability properties of walls to moisture accumulation within uninsulated as well as insulated walls, particularly those which lend themselves to use of fill-type insulation.

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[1] Project 541 of the Iowa Agricultural Experiment Station. Taken from a thesis submitted to the faculty of the Graduate College, Iowa State College, in partial fulfillment of the requirements for the degree doctor of philosophy.

[2] The author wishes to express his sincere appreciation for the helpful suggestions and encouragement received from numerous sources, particularly the following:

- Dr. J. B. Davidson, head, Prof. Henry Giese, Dr. E. G. McKibben and other members of the Agricultural Engineering Department.
- Dr. J. W. Woodrow, head, Dr. Harold Stiles and other members of the Physics Department.
- Dr. D. L. Holl, Profs. R. A. Norman and R. A. Caughey, members of the committee in charge of the author's graduate work.
- Prof. W. M. Dunagan of the Theoretical and Applied Mechanics Department.
- Mr. L. V. Teesdale of the U. S. Forest Products Laboratory, Madison, Wis.

REVIEW OF LITERATURE

Experiments are being conducted on the condensation of moisture in walls by the U. S. Forest Products Laboratory at Madison, Wis., and the Engineering Experiment Station at the University of Minnesota. Preliminary and progress reports of these studies have been published. Other investigations relating to this subject apply to insulation for refrigerators and refrigerated rooms, where the moisture problem has been known for some time.

Rowley and others (12) at the Minnesota Engineering Experiment Station have recently reported some of their findings on small test houses representing various types of frame-wall construction. Their results show that frost accumulated on the inside surface of the sheathing from five to six times as rapidly in an insulated wall as in a wall of the same construction without fill insulation. However, the rate of accumulation of moisture in the insulated wall may be reduced considerably by placing a moisture barrier, either in the form of a highly vapor-resistant paper between the plaster and the inside face of the studs or by the application of one or more coats of vapor-resistant paint, on the inside surface of the plaster. The asphalt-impregnated papers and the asphalt and the aluminum paints were found to be highly resistant to the transfer of water vapor, as determined by their effectiveness in reducing the rate of moisture accumulation.

Tests on other wall sections without vapor seals showed the amounts of condensation to be independent of the type of fill insulation used.

Teesdale (13) and Dunlap (4) of the U. S. Forest Products Laboratory have been conducting rather extensive studies on condensation of moisture within walls. The latter is observing not only the amount of moisture retained in the walls, subjected to carefully controlled conditions, but also the amount passing through. In addition, observations are being made on changes in the rate of heat transfer through the wall as condensation progresses. The results as yet have not been reported.

Teesdale (13) has been making tests on the vapor resistance of various materials used in wall construction and on those materials which might be used for moisture barriers. He states that moisture accumulation is influenced by the following factors: (a) Outside temperature and humidity, (b) efficiency of insulation, (c) inside temperature and humidity, (d) resistance of outer wall to vapor movement and (e) resistance of inner wall to vapor movement.

In his report he sets forth general recommendations to lessen the chances of moisture accumulation. These include the application of a vapor barrier on or in the warm side of the wall and ceiling, the ventilation of the attic and the reduction of humidities in existing houses during cold weather.

Edgar (5) has observed that fill insulation placed between two layers of reinforced waterproof paper in walls of potato storage structures had accumulated considerable moisture during the storage season. The amount of accumulation was less, however, when the wall was vented at the plate to the cold side.

In connection with some investigations on insulation in refrigerator walls, McPherson (8) (9) reveals the following significant facts: (a) Moisture accumulation in loose-fill thermal insulants in walls of refrigerators will occur if the temperature of the inside surface of the interior walls is at or below the dew point, unless the materials are dehydrated and the walls tightly sealed; (b) if there is an appreciable infiltration of air through the outside walls, moisture accumulation will continue indefinitely, even after the insulation and wall become wet. If, however, the lowest temperature in the wall is above the dew point, there is a loss of moisture.

In 1932, Berestneff (1) pointed out that methods of moisture-proofing refrigeration insulation should be investigated to properly safeguard against moisture accumulation through infiltration of water vapor.

Rees (11) has emphasized the principle of providing free ventilation between the insulation and the cold air, in the use of fill insulation in refrigerated rooms.

Hukill (6) states that the problem of preventing condensation in a wall is one of keeping the dew point of the atmosphere at any place in the wall below the actual temperature at that point. He emphasizes the use of a good moisture barrier on the warm side of the wall and the provision of as little resistance as possible to the passage of water vapor on the cold side.

A review of the literature would appear to warrant the following conclusions:

1. A fundamental principle in preventing accumulation of moisture is to place the moisture barrier on or in the warm side of the wall rather than the cold side where it is so often placed.

2. Ventilation of the cold wall to the cold side either by small openings or by venting the space formed by keeping the insulation from contacting the cold wall offers some possibilities in preventing condensation.

3. In addition to the environmental conditions to which the wall is subjected, the thermal and water vapor permeability properties of the warm and cold sides of the wall and the insulation are factors which determine the rate of moisture accumulation.

4. Insulated walls may accumulate moisture more rapidly than uninsulated walls.
5. The rate of condensation within an insulated wall is independent of the kind of fill insulation used.

THE INVESTIGATION

The study was confined to a consideration of uninsulated and insulated walls, with special reference to fill-type insulation. The principal objectives of this investigation were as follows: (a) To determine the relation of the thermal and water vapor

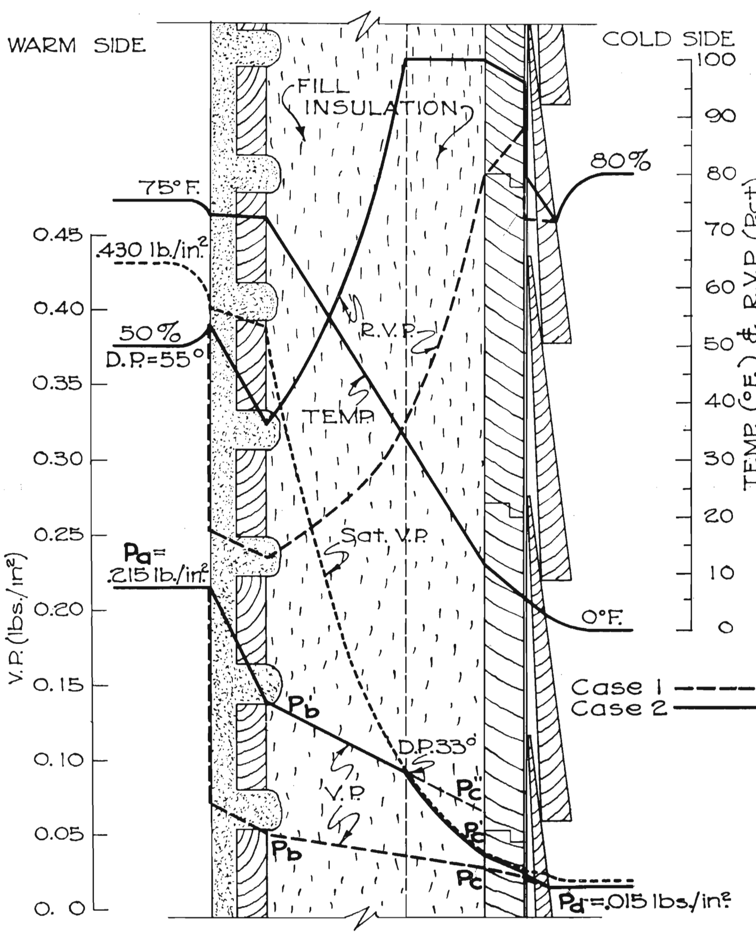


Fig. 1. A cross section of a typical frame wall showing conditions assumed in an analysis of moisture accumulation.

permeability properties of walls to moisture accumulation and (b) to determine the permeability of wall materials to water vapor. In the former, analytical as well as experimental methods were employed.

AN ANALYSIS OF MOISTURE ACCUMULATION WITHIN WALLS

The problem of moisture accumulation within walls involves the transfer or flow of water vapor through mediums. Building materials used for wall construction exhibit widely varying properties in their resistance to the flow of water vapor. An improper selection and combination of these materials in wall construction from the standpoint of vapor transfer under certain temperature and vapor pressure differences may result in moisture accumulation.

CONDITIONS ASSUMED

An analysis can perhaps best be made by assuming a rather typical condition of temperatures and humidities to which a wall may be subjected. The illustration in fig. 1 shows a conventional frame wall with fill insulation subjected to a temperature of 75°F. and relative humidity of 50 percent on the warm side and 0°F. and 80 percent relative humidity on the cold side. A consideration of Dalton's Law of Partial Pressures shows that the partial pressure of the water vapor is higher on the warm side than that on the cold side. The magnitudes of these pressures may be determined conveniently from the accompanying chart (fig. 2) prepared from published tables of saturated vapor pressures of water and ice (7) (10). The curves at various percentages of saturation are also shown. Referring to the chart, the partial vapor pressures on the warm and cold sides of the wall are .215 and .015 lbs./in.^{2}, respectively. Hence, the wall is subjected to a difference in vapor pressure of .2 lb./in.^{2}

If the wall is permeable, water vapor will flow to the right by virtue of the difference in vapor pressure on the two sides of the wall. This flow takes place by diffusion even in still air. Thus, it is not necessary that the other gases in the air flow with the vapor in order for its transfer to take place. The vapor pressure gradient across the wall will depend on the relative vapor resistance or the permeability of each of the component parts of the wall.

Two cases of flow of water vapor through the wall will be discussed; namely, case 1 with no accumulation and case 2 with an accumulation of moisture in the wall. The temperatures and vapor pressures on both sides of the wall are the same in each case. The same is true for the temperature gradient which has been calculated from known thermal conductivity data. Fur-

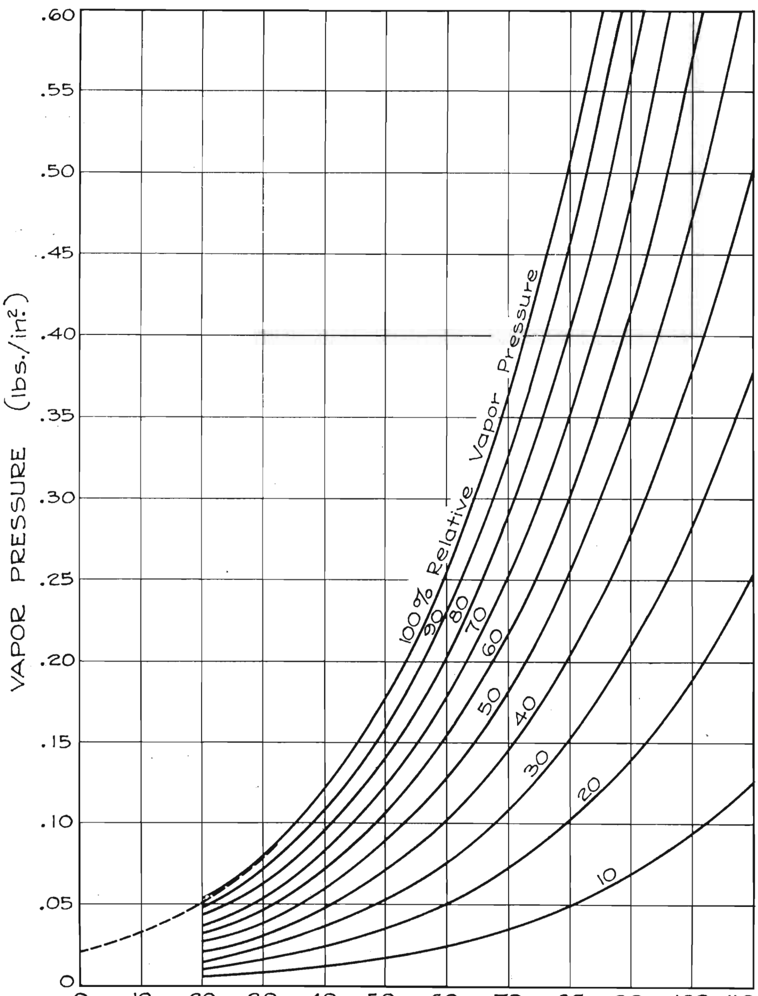


Fig. 2. Vapor pressure-temperature relationships for water vapor, 0° to 110° F.

ther, the gradient of the vapor pressures at saturation is the same in both cases, since it is dependent on the temperature gradient. The two cases differ only in the relative resistance which the warm side of the wall offers to the flow of water vapor.

In case 1 the resistance is considered to be high, a condition which may be produced by placing, for example, a relatively impermeable membrane on the surface of the warm side of the wall. The drop in vapor pressure across the warm side of the wall is then large as shown by the broken line in fig. 1, and the pressures throughout the remainder of the wall are low, never reaching saturation pressure or the dew point. The degree to which they approach saturation is indicated by the corresponding relative humidity gradient and also by the differences in values of the actual and saturation vapor pressures at each point in the wall.

In case 2, with a lower resistance to the flow of vapor across the same part of the wall, the drop in pressure across the warm side of the wall will not be as great, and the vapor flows across the insulation under higher pressures than in case 1, so that saturation pressures may more readily be reached, as indicated by the difference in the actual and saturated vapor pressures and also by the corresponding relative humidity gradient. With the assumed vapor pressure gradient, the saturation pressure (dew point) is reached at 33°F. to the right of which the pressures are also those of saturation shown by the curved portion of the vapor pressure gradient. However, numerous observations indicate that water vapor does not condense within the fill insulation but is found at the boundary of the insulation and on the cold side of the wall. Such observations would appear to show that the actual vapor pressure gradient is below that indicated in the illustration.

This discussion need not concern itself necessarily with the probable gradient but rather with the vapor pressures at the boundaries of the insulation, which are needed for expressions for the flow of water vapor through the wall.

Notation

M. Weight of water vapor transmitted per unit wall area per unit of time.

M_a. Weight of moisture retained in wall per unit area per unit of time.

P_a. Vapor pressure on warm side of wall.

P_b. Vapor pressure between warm side of wall and fill insulation.

P_c. Vapor pressure between fill insulation and cold wall.

P_d. Vapor pressure on cold side of wall.

K_a, K_b and K_c. Water vapor permeabilities of the warm side of wall, the fill insulation and cold side of wall, respectively.

Water vapor permeability is the constant of proportionality relating the rate of water vapor transmitted to the vapor pressure difference. It varies with different materials and is the amount of water vapor transmitted per unit area per unit of time per unit of vapor pressure difference. Its reciprocal expresses the resistance to the flow of vapor and is frequently referred to as "vapor resistance."

In case 1 the symbols are unprimed; in case 2 they have been primed only where their values differ from those in case 1.

EXPRESSIONS FOR FLOW OF VAPOR

Assuming that the weight of water vapor transmitted is proportional to the vapor pressure difference (2), under all conditions under consideration, the rate at which the water vapor flows through the wall in case 1 can be expressed as follows:

$$M = K_a(P_a - P_b) = K_b(P_b - P_c) = K_c(P_c - P_d),$$

or

$$M = K_d(P_a - P_d), \text{ where} \tag{a}$$

$$\frac{1}{K_d} = \frac{1}{K_a} + \frac{1}{K_b} + \frac{1}{K_c}.$$

All of the vapor which flows into the wall flows out, and each part of the wall produces a drop in vapor pressure proportional to its vapor resistance. As noted above, none of the pressures reach saturation at any point in the wall, due largely to the fact that the resistance on the warm side of the wall is very high, producing a large drop in pressure across the warm side of the wall.

If in case 2, with less vapor resistance on the warm side, no moisture accumulation for the moment is assumed the following expression similar to the one above would hold,

$$M' = K'_a(P_a - P'_b) = K_b(P'_b - P''_c) = K_c(P''_c - P_d)$$

$$M' = K'_d(P_a - P_d), \text{ where} \tag{b}$$

$$\frac{1}{K'_d} = \frac{1}{K'_a} + \frac{1}{K_b} + \frac{1}{K_c}.$$

P''_c is the vapor pressure necessary at the boundary of the fill insulation and the cold wall to prevent condensation. However, the maximum pressure which can exist at this boundary is the saturation pressure P'_c determined by the temperature at that point. Then the vapor flowing through the cold side of the wall is

$$K_c(P'_c - P_d),$$

and the amount of moisture accumulating in the wall (M_a) is given by the expression,

$$M_a = M' - K_c(P'_c - P_d). \tag{c}$$

It should be noted that in the expression $K_c(P'_c - P_d)$, since P'_c does not vary (except for slight increases due to a rise in temperature from the heat of condensation), the rate of flow through the outside wall is constant and therefore is independent of the flow M' providing condensation in the wall is taking place. The flow M' into the wall is then independent of the amount flowing out, but is dependent on the rate at which the vapor condenses in the wall. In the special case where the cold side of the wall has zero permeability it is equal to the rate of condensation.

The rate at which the water vapor condenses within the wall is determined by the rate at which the heat of condensation (also fusion if temperatures are below freezing) is dissipated in the wall. The condensation may in effect be considered to be equivalent to vapor flowing through a layer of material with vapor resistance placed at the corresponding point in the wall at which condensation takes place.

RELATION OF VAPOR PERMEABILITY OF WALLS TO MOISTURE ACCUMULATION

The expression for the rate of moisture accumulation in the wall becomes,

$$M_a = \frac{K'_a K_b}{K'_a + K_b}(P_a - P'_c) - K_c(P'_c - P_a), \tag{d}$$

when the expression for M' given between the pressure $P_a - P'_c$ is substituted in equation (c).

For the condition when no moisture accumulation occurs within the wall, $M_a = 0$. Setting equation (d) equal to zero and solving for the ratio of the permeability of the cold side of the wall to that of the warm side,

$$\frac{K_c}{K'_a} = \frac{P_a - P'_c}{P'_c - P_d} - \frac{K_c}{K_b}. \tag{e}$$

Since the permeability of fill insulation K_b is large and the permeabilities of the warm and cold sides of the walls are relatively small, the last term K_c/K_b may be neglected and the pressure P'_b approaches P'_c. The ratio K_c/K'_a then becomes

$$\frac{P_a - P'_c}{P'_c - P_d},$$

which shows that the ratio of the permeabilities of the warm and cold sides of the wall are inversely proportional to the ratio of the vapor pressures across the respective walls.

The ratio must be high to prevent condensation even at ordinary conditions. For example, for the wall and conditions given in fig. 1, the ratio must be 18 or greater. With a relative humidity of 35 percent on the warm side of the wall, the ratio must be 12 and with a relative humidity of 65 percent, it must be 24 to prevent condensation.

When the permeability K_c of the cold side of the wall is high, the ratio K_c/K'_a may be smaller by the amount K_c/K_b.

An inspection of equation (d) shows also that when moisture is accumulating by condensation the rate of accumulation increases with an increase in permeability K'_a of the warm side of the wall and decreases with an increase in permeability K_c of the cold side of the wall.

The location of an impermeable membrane or ''moisture barrier'' to prevent accumulation of moisture in the wall should be to the left of the isothermal plane in the wall, the temperature of which is just above the dew point of the air on the warm side of the wall. If it were located to the right of the dew point temperature, an accumulation might take place, depending on the permeability of the barrier; in fact, the cold side of the wall constitutes a moisture barrier when its permeability is less than that of the insulation. For extreme conditions the barrier should be placed on the surface of the warm side of the wall.

RELATION OF THERMAL PROPERTIES OF WALLS TO MOISTURE ACCUMULATION

It was pointed out that the surface temperature of the warm side of a moisture barrier is an important factor in determining whether moisture accumulation is possible. In ordinary walls the surface temperature of the inside of the cold side of the wall should be considered, since this side constitutes a moisture barrier as mentioned.

The temperature t_c at this point is expressed by the following equation, which can readily be derived from heat flow equations through the wall,

$$t_c = \frac{U}{U_c}(t_a - t_d) + t_d, \text{ where}$$

t_a and t_d are the temperatures on the warm and cold sides, respectively, and U and U_c are the thermal transmittance coefficients of the whole wall and the cold side of the wall, respectively.

This expression shows that the temperature increases with U and decreases with U_c. It shows also that this temperature is much lower in an insulated wall than in an uninsulated wall. Further, to increase the temperature by adding insulation to the cold side of the wall is not nearly as effective in an insulated wall as is the case in an uninsulated wall.

RELATION OF ENVIRONMENTAL CONDITIONS TO MOISTURE ACCUMULATION

The temperatures and vapor pressures on both sides of the wall are primary factors in the accumulation of moisture in the wall. In order for condensation to take place in the wall, the conditions must be such that temperatures within the wall are below the dew point of the air on the warm side of the wall.

Equation (d) shows that the rate of moisture accumulation increases with the vapor pressure P_a on the warm side of the wall and decreases with the pressure P_d on the sold side of the wall. As already pointed out above, the temperature t_c determines the pressure P'_c. Hence, the rate of accumulation increases with a decrease in temperature on the inside of the cold side of the wall.

CONCLUSIONS

1. The factors which influence the condensation of moisture in walls are:
   - a. Temperatures and vapor pressures on both sides of the wall.
   - b. Water vapor permeability of the warm and cold sides of the wall.
   - c. Thermal properties of the component parts of the wall.
2. The necessary condition for condensation of moisture to take place within a wall subjected to a temperature difference is that the temperature at some point in the wall must be below the dew point of the air on the warm side of the wall.
3. The rate of accumulation of moisture in a wall increases with the permeability of the warm side of the wall and decreases with that of the cold side of the wall.
4. For zero accumulation, the permeability of the cold side of the wall must be many times that of the warm side. The ratio depends on the temperature and vapor pressure differences to which the wall is subjected.
5. A vapor barrier used to prevent condensation in a wall, should be located on the warm side of the isothermal plane in the

wall, the temperature of which is at or above the dew point of the air on the warm side. For extreme conditions it should be placed on the surface of the warm side of the wall.

6. The overall thermal transmittance of the wall and the thermal conductance of the component parts of the wall affect the rate of accumulation of moisture, in so far as the temperature on the inside of the cold side of the wall is influenced.

WATER VAPOR PERMEABILITY MEASUREMENTS

A number of methods have been used by different investigators (2) in determining the permeability of such materials as paint films, wrapping and packaging materials. Although the same or similar methods could be used for measuring the permeability of wall materials, no results have been published. However, the Forest Products Laboratory (13) has been conducting rather extensive tests on a large number of building materials for wall construction.

The various methods employed and the factors influencing water vapor permeability measurements of materials other than those for buildings have been reviewed by Carson (2) of the National Bureau of Standards. Although the test conditions, procedures and units of permeability used vary widely, the methods of determining the water vapor permeability are relatively few.

From a review of methods of measurement on other materials, it would appear that relative humidity at the faces of the specimen is a principal factor to be considered in determining the water vapor permeability of building materials. In general, for conditions where the relative humidity does not exceed 75 percent, the amount of water vapor transmitted varies directly with the

TABLE 1. TEMPERATURES AND REAGENTS USED TO OBTAIN VAPOR PRESSURE DIFFERENCES FOR PERMEABILITY TESTS.

Method	High pressure side				Low pressure side				Vapor pressure difference
	Reagent	Temp.	R. H.	Vapor pressure	Reagent	Temp.	R. H.	Vapor pressure	
		°F.	Pct.	lbs./in.^{2}		°F.	Pct.	lbs./in.^{2}	lbs./in.^{2}
A	NaCl	75	75	.322	Room	75	50	.215	.107
B	H_2O	75	100	.429	Room	75	50	.215	.214
C	Room	75	50	.215	H_2O	32	100	.089	.126
D	H_2O	75	100	.429	H_2O	32	100	.089	.340

vapor pressure difference. Above 75 percent the amount transferred per unit vapor pressure difference is greater.

METHODS OF MEASUREMENT

Several methods were used in making permeability measurements, in order (a) to obtain determinations on a wide variety of materials, (b) to check permeability measurements by different methods and (c) to make measurements under conditions which approach those in a wall. The methods used are identified by the letters A to D, inclusive, and each will be described on the following pages. The reagents and temperatures used to obtain various vapor pressure differences in each of the methods are given in table 1.

METHOD A

In this method the specimens were sealed onto the tops of the shallow trays or pans made of light sheet metal or heavy tinned sheet iron of the shape and size shown in fig. 3. The pans were partly filled through the copper tubing with a concentrated solution of NaCl giving a relative humidity of 75 percent under the specimen. After the tubes were sealed with wax, the pans were placed in the constant temperature-humidity room in which a temperature and relative humidity were maintained at 75° F. and 50 percent, respectively. A vapor pressure difference of .107 lbs./in.^{2} was provided in this manner across the faces of the specimen. The amount of vapor transpired could be determined by weighing the pan with its contents at 1 or 2-day intervals.

To insure against edge leakage and to reduce edge effects to a minimum, thick and thin specimens were sealed in the trays in different manners. In case of the latter, the specimens were placed in a light metal frame of tinned sheet iron (fig. 3), the inside dimensions of which were 10 inches square. They were sealed in the frame by filling the channel of the frame with melted wax consisting of equal parts of beeswax and rosin, readily accomplished with the use of an eye dropper. This gave a good edge seal and, in addition, permitted a rather definite area to be exposed.

Specimens over ¼-inch thick were first sealed at all four edges with wax. Wood fillers soaked in melted wax were then fused to each of the four edges of the specimen.

The manner of sealing the thick and thin specimens to the pan was the same for both and was accomplished by placing them in the pans and simply dipping each of the pan's edges in melted wax. This gave an excellent seal.

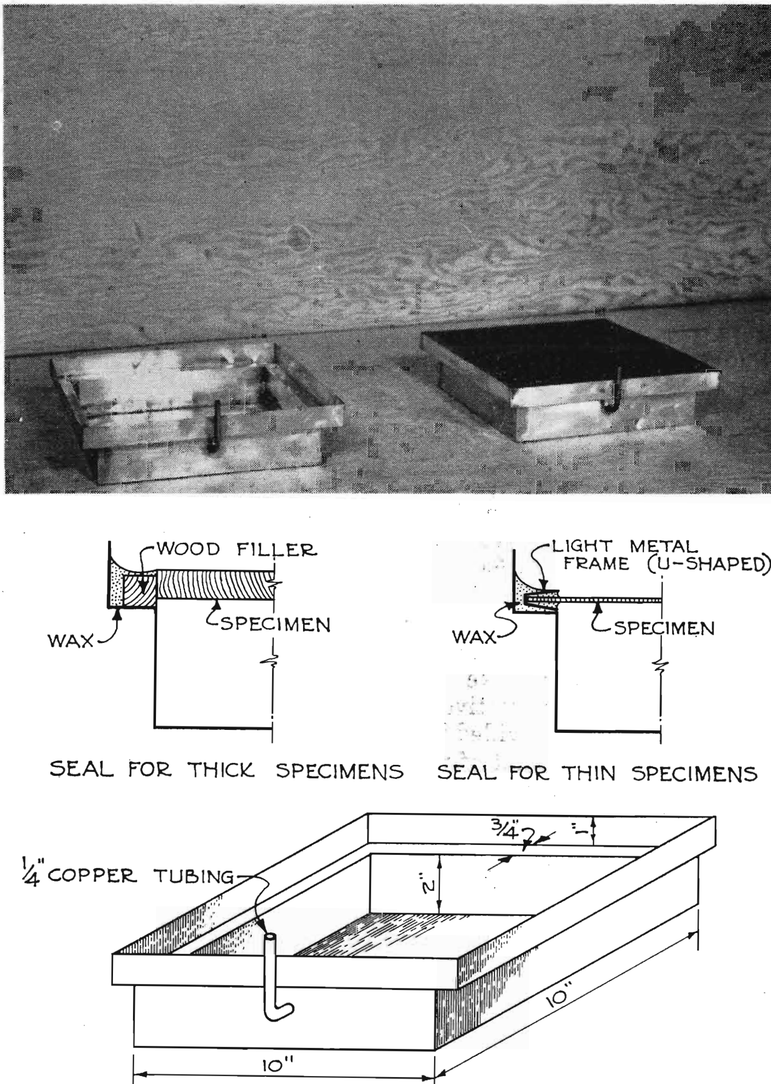


Fig. 3. Pans used in methods A and B for water vapor permeability measurements (photo shows pans with and without specimen).

METHOD B

This method is the same as A except that water was used for the reagent. The water supplied a relative humidity of 100 percent on the underside of the specimen, giving a vapor pressure difference of .214 lbs./in.^{2} across the specimen when placed in the room with conditions at 75° F. and 50 percent relative humidity. This method was used to compare the permeability of specimens under higher vapor pressure differences and higher relative humidities.

METHOD C

This method which provides vapor pressure differences through differences in temperatures can be used to measure the permeability of heavy specimens which cannot readily be determined with the above methods because of the difficulty of measuring small changes in weight with such large weights. The specimens are sealed in place much in the same manner as in the above methods. The cold surface maintained at a temperature of the mixture of ice and water of 32° F. provided a vapor pressure of .089 lbs./in.^{2}, giving a difference of pressure of .126 lbs./in.^{2} across the specimen. The amount of water vapor permeating was condensed on the cold surface and collected in 200 cc. beakers which were weighed at intervals of a day or two. The construction of the apparatus and the manner in which it was placed over the coils is shown in fig. 4. By placing it over the cooling coils, the apparatus could be operated with the use of much less ice.

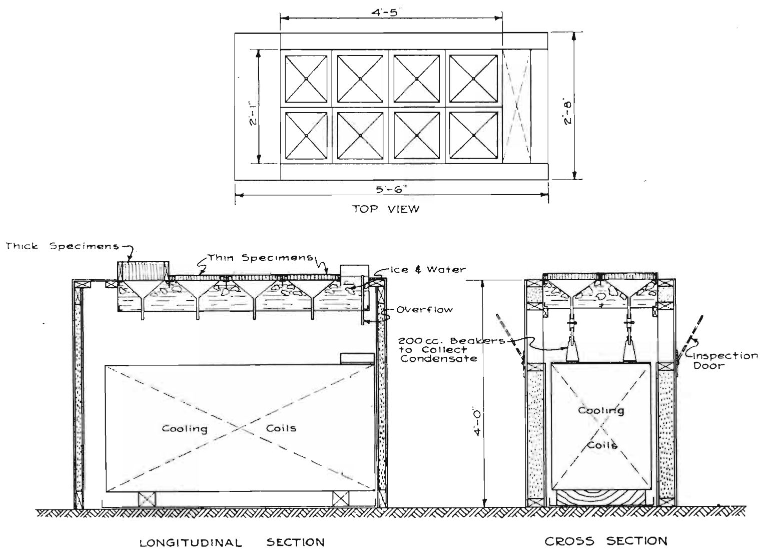
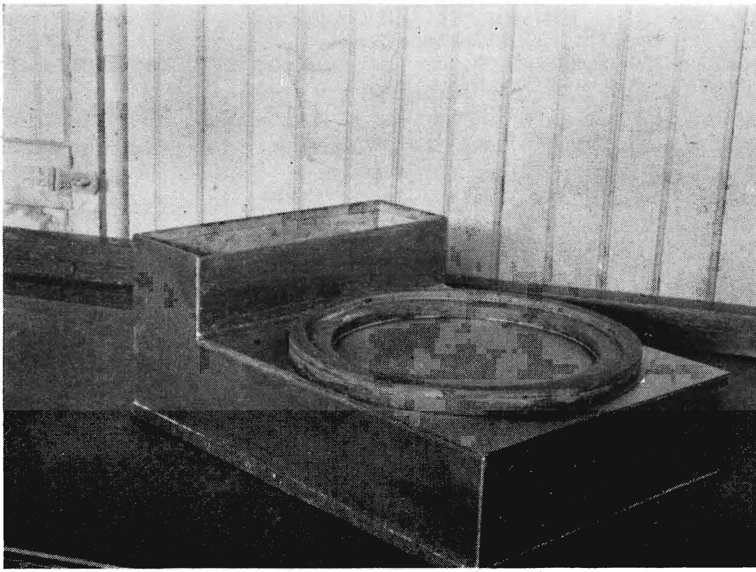
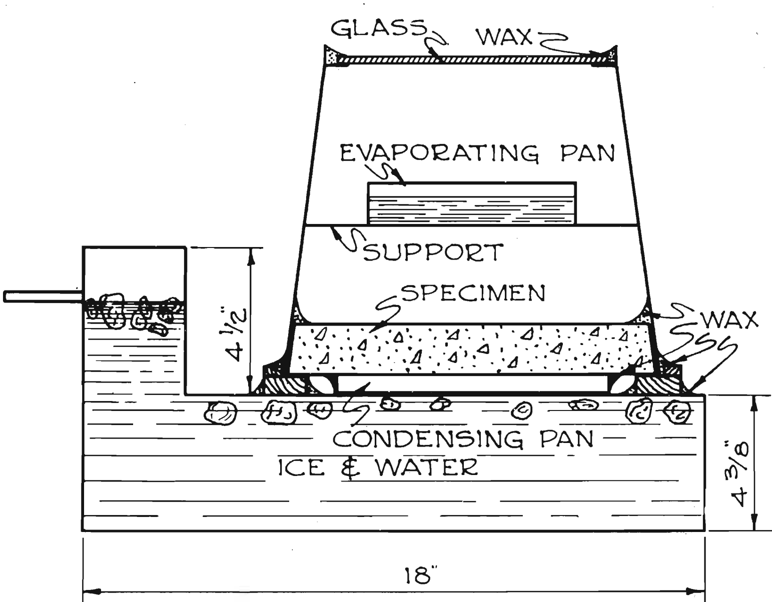


Fig. 4. Apparatus used in method C for water vapor permeability measurements.





VERTICAL SECTION

Fig. 5. Apparatus used in method D for water vapoi permeability measurements.

METHOD D

This method is very similar to the previous one, except that the humidity or vapor pressure above the specimen may be altered and made independent of the room by placing a reagent in the evaporating pan inside of the inverted container sealed over the specimen. In it, the guard ring principle is employed, and it enables one to check the amount of water vapor permeated by the amount of water evaporated from the pan. The apparatus is shown in fig. 5.

RESULTS

The unit used to express the water vapor permeability of the different materials tested was in gms./ft.^{2} Da. lb./in.^{2} vapor pressure difference. Typical curves showing the accumulated amount of water vapor transmitted for specimens of both high and low permeability as determined by method A and other specimens as determined by method C are illustrated in figs. 6 and 7, respectively. The slopes of the straight line portions of the curves give the average rate of loss per day, which together with the vapor pressure difference and the area of the specimen enable one to determine the permeability by simple calculation. By using the slopes of the linear portion of the curve, the effect of the conditioning period at the beginning of the test is elim-

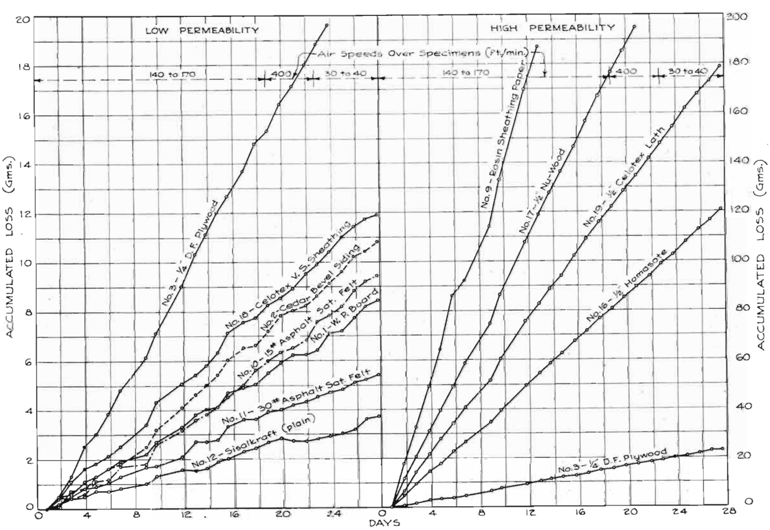


Fig. 6. Accumulated amounts of water vapor transmitted by method A through specimens of low and high permeability.

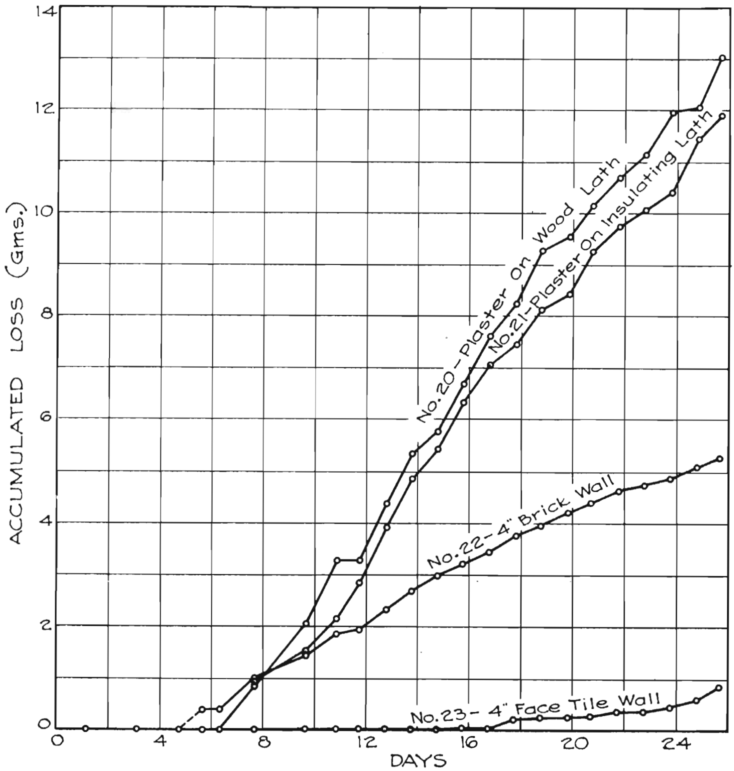


Fig. 7. Accumulated amounts of water vapor transmitted through specimens by method C.

inated. Most of the variations from the average slope of the specimens of low permeability are attributable to variations in weighing, which were not so marked with those of higher permeability. The variations in method C are largely due to the nature of flow of the condensate from the condensing surfaces, which comes at more or less irregular intervals. The conditioning period was much longer for the specimens by method C than by either method A or B, because, in addition to the moisture which the material would absorb, a certain amount of moisture had to be condensed first before flow would take place.

The effect of the rate of air movement as determined by a Hukill hot-wire anemometer over the top surface of the specimens was apparently negligible. In fig. 6 the slopes of the curves, i.e., the rate of moisture loss did not appear to change with the variations in air speeds indicated for the respective portions of the test period.

The results of the permeability measurements of the various materials tested are summarized in table 2 and shown in graphical form in fig. 8. The numbers with letters indicate that the same specimen has been used. The difference is either in treatment or method of test.

COMPARISON OF MATERIALS

The results show a wide range of properties, which different materials used in building construction have, relative to their resistance to the flow of water vapor. Even within the same class of materials, a wide variation may exist, as in the case of building papers. Rosin sheathing paper shows a permeability of 192 in contrast to the asphalt-saturated felts and sisalkrafts which show only a permeability of 1.7 to 4.2. A ¾-inch white pine board and a section of cedar bevel siding also show low permeabilities of 4.4 to 5.7, respectively. Plywoods show somewhat higher permeabilities than the boards.

The common fiber insulation boards and insulating lath show very high permeabilities. With moisture proofing of such boards as specimen 18, the permeability may be reduced to the equivalent of wood boards. Plaster on either wood or insulating lath permits appreciable moisture to flow through as revealed by the tests which show permeabilities from 7 to 15

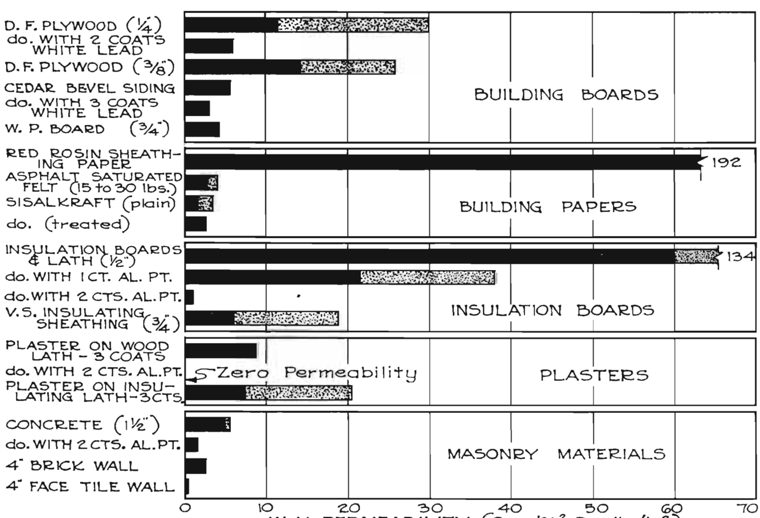


Fig. 8. Water vapor permeabilities of different kinds of building materials tested. (The range in variation in different specimens and method of measurement are given by the light portions of the bars.)

TABLE 2. SUMMARY OF PERMEABILITY TEST DATA.

Specimen				Test			Moisture transmitted			Water vapor permeability
No.	Description	Area	Thickness	Method	Duration	Vapor pres. difference	Total	Rate		
		in.²	in.		days	lbs./in.²	Gms.	Gms./Da.	Gms./Da. ft.²	Gms./Da. ft.² lb./in.²
		Building boards								
1	White Pine board	100	3/4	A	28	.107	9.4	.327	.471	4.40
2	Cedar bevel siding	100	—	A	28	.107	10.8	.426	.614	5.74
2a	do. with three coats white lead paint	100	—	A	28	.107	7.6	.238	.343	3.21
3	Douglas Fir plywood (G2S)	100	1/4	A	28	.107	23.0	.866	1.247	11.63
3a	do. with two coats white lead paint	100	1/4	A	17	.107	6.6	.457	.658	6.15
4	Douglas Fir plywood (G2S)	100	1/4	A	23	.107	20.8	1.05	1.51	14.1
5	do.	100	1/4	B	23	.215	91.6	4.28	6.17	30.1
6	do.	100	3/8	A	15	.107	14.4	1.06	1.52	14.3
7	do.	49.4	3/8	D	13	.102	11.8	.907	2.65	25.9
8	do.	100	3/8	B	23	.215	65.8	3.18	4.58	21.3
		Building papers								
9	Red rosin sheathing paper	100	—	A	28	.107	407.2	14.22	20.50	191.5
10	Asphalt-saturated felt (15 lb.)	100	—	A	28	.107	18.4	.314	.452	4.23
11	do. (30 lb.)	100	—	A	28	.107	5.4	.208	.300	2.80
12	Sisalkraft (plain)	100	—	A	28	.107	3.7	.135	.194	1.82
13	do.	100	—	B	23	.215	12.2	.550	.792	3.68
14	do.	100	—	A	23	.107	2.9	.126	.181	1.69
15	Sisalkraft (treated)	100	—	B	23	.215	9.5	.390	.561	2.61
		Insulation boards								
16	Homasote	100	1/2	A	28	.107	120.1	4.48	6.45	60.3
16a	do. with one coat aluminum paint	100	1/2	A	14	.107	40.9	2.84	4.08	38.2
16b	do. with two coats aluminum paint	100	1/2	A	11	.107	0			0
17	Nu-wood	100	1/2	A	28	.107	254.8	9.97	14.34	134.2
17a	do.	100	1/2	B	14	.215	251.8	18.85	27.15	126.2
18	Celotex vapor-seal insulating sheathing	100	25/32	A	28	.107	11.9	.461	.615	6.20
18a	do.	100	25/32	B	15	.215	18.5	1.41	2.03	18.98
19	Celotex insulating lath	100	1/2	A	28	.107	178.4	6.72	9.67	90.4
19a	do. with one coat aluminum paint	100	1/2	A	14	.107	22.7	1.61	2.32	21.7
19b	do. with two coats aluminum paint	100	1/2	A	47	.107	2.4	.083	.12	1.12

TABLE 2. SUMMARY OF PERMEABILITY TEST DATA.—(Continued)

Specimen				Test			Moisture transmitted			Water vapor permeability
No.	Description	Area	Thickness	Method	Duration	Vapor pres. difference	Total	Rate		
		in.²	in.		days	lbs./in.²	Gms.	Gms./Da.	Gms./Da. ft.²	Gms./Da. ft.² lb./in.²
	Plasters									
20	Plaster on wood lath (three coats)	100	3/4	C	26	.126	13.0	.672	.967	9.04
20a	do. with two coats aluminum paint	100	3/4	A	14	.107	0			0
21	Plaster on insulating Celotex lath (3 coats)	100	3/4	C	26	.126	11.91	.645	.928	7.36
21a	do.	100	3/4	A	14	.107	12.8	1.10	1.58	14.8
21b	do.	100	3/4	B	23	.215	61.4	2.95	4.25	20.7
	Masonry materials									
22	Brick wall section laid up with mortar	111	4	C	26	.126	5.30	.243	.315	2.50
23	Tile wall section laid up with mortar	121	4	C	26	.126	.61	.041	.049	.39
24	Concrete	100	1 1/2	C	26	.102	6.5	.372	.535	5.25
25	do.	48	1 1/2	A	27	.107	4.8	.20	.60	5.56
26	do. with two coats aluminum paint	48	1 1/2	B	22	.215	2.4	.115	.345	1.60
27	do. with two coats liquid coating asphalt	48	1 1/2	A	22	.107	2.2	.177	.53	4.95
	Fill insulation									
28	Ground cornstalks	100	2	A	10	.107	87.7	9.88	14.2	133.0
29	Rock wool	100	1	A	10	.107	53.7	6.00	8.64	80.7
30	Sawdust (D.F.)	100	2	B	21	.215	294	14.9	21.5	100
	Miscellaneous									
31	Tin sheet (for checking wax seal)	100	—	A	28	.107	.2			0
31a	do. with four 1/16" holes	100	—	A	17	.107	4.8	.392	.565	5.28
32	Evaporation from free surface (NaCl Sol.)	100	—	A	3.54	.107	507	143	206.	1925

gms./ft.^{2} Da. lb./in.^{2} vapor pressure difference. Brick and tile walls, and concrete all transmit appreciable quantities of water vapor.

EFFECT OF PAINT

The effect of the application of one or more coats of white lead and aluminum paint is shown by the results on specimens 2a, 3a, 16a, 18a, 19b, 20a, 26 and 27. Although two coats of white lead reduced the permeability of the ¼-inch plywood specimen 3 from 12 to 6, the aluminum paint is much more effective, especially when two coats are applied. It was even very effective on insulation boards, reducing their permeability by ½ to ¼ with the application of one coat, and still a greater reduction was produced with the application of two coats. No moisture loss was detectable through the plaster on wood lath with two coats of aluminum paint.

COMPARISON OF METHODS

The results show a rather wide variation in the permeabilities of the same material as determined by the different methods employed. The results by method B are much higher for the specimens of low permeability than by method A. For specimens of high permeability the reverse is true. For example, the determination for specimen 18 was three times larger with method A than B. However, with a specimen of high permeability like 17 the determinations by methods A and B were 134 and 126 gms./ft.^{2} Da. lb./in.^{2}, respectively. Another good comparison of the methods was obtained by the determinations of the ⅜-inch plywood specimens. The permeabilities obtained were 14.3, 21.3 and 25.9 gms./ft.^{2} Da. lb./in.^{2} by methods A, B and D, respectively. These results show the effect of higher relative humidities on the unit of permeability, which is in agreement with results obtained on papers by Charch and Scroggie (3).

Method C gave considerable lower values for permeability than method A. The comparison is given by the plaster sample 21, for which the value is 7.4 by method C and 14.8 by method A.

HYGROSCOPICITY MEASUREMENTS

In order to determine possible relationships of the hygroscopicity of the fill insulation to moisture accumulation, measurements of the equilibrium moisture contents at various relative humidities were made. The data were also of considerable value in determining the relative and absolute vapor pressure gradients within the various layers of insulation in the test walls.

To determine the hygroscopicity of various fill insulating materials, the method known as the "stirred chamber" was used.

The apparatus consisted of a suitable metal container in which sulphuric acid of various dilutions (15) in jars supplied the desired humidities. The samples were placed in open petri dishes on wire mesh shelves above the solutions. The air was stirred by a slow-running electric fan.

The results of the hygroscopicity determinations are given in table 3 and are shown in graphical form in fig. 9. It is apparent

TABLE 3. EQUILIBRIUM MOISTURE CONTENTS (PCT.) OF FILL INSULATING MATERIALS AT VARIOUS RELATIVE HUMIDITIES AT 80°F.

Relative humidity (pct.)		20	35	50	65	80	93
Material	Cornstalks (ground)	6.73	8.41	10.6	12.8	18.0	
	do.	7.35	8.80	11.0	13.2	18.6	30.8
	do.	6.52	8.05	10.0	12.2	17.8	
	Sawdust (D.F.)	5.08	6.57	8.09	9.59	12.6	19.2
	Vermiculites (expanded)	.04	.05	.05	.05	.06	.11
	Rock wool	0	0	0	0	0	.01

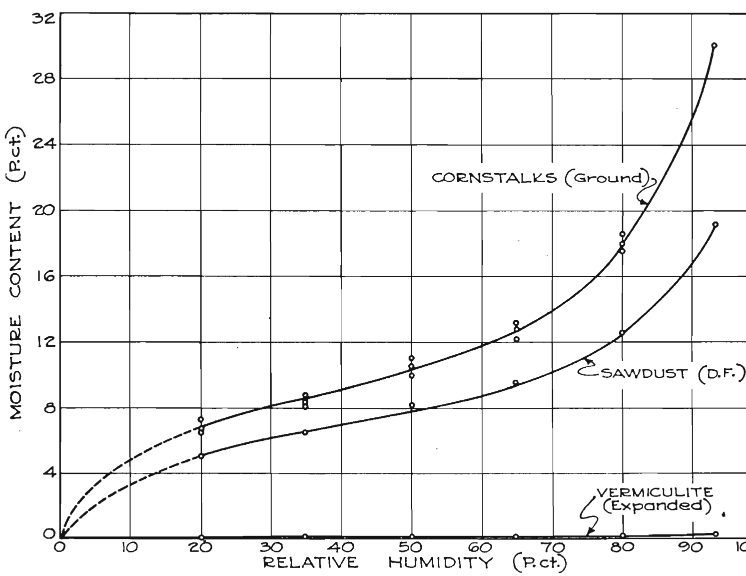
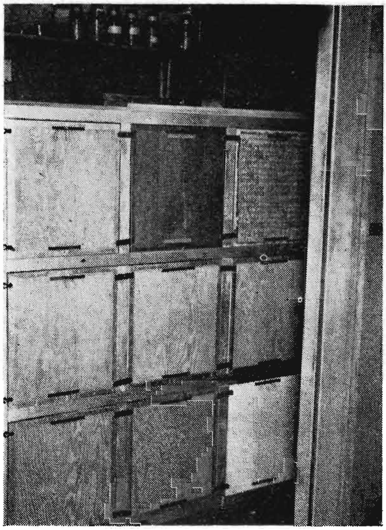


Fig. 9. Equilibrium moisture contents of fill insulating materials at various relative humidities at 80° F. Moisture content is on dry basis.



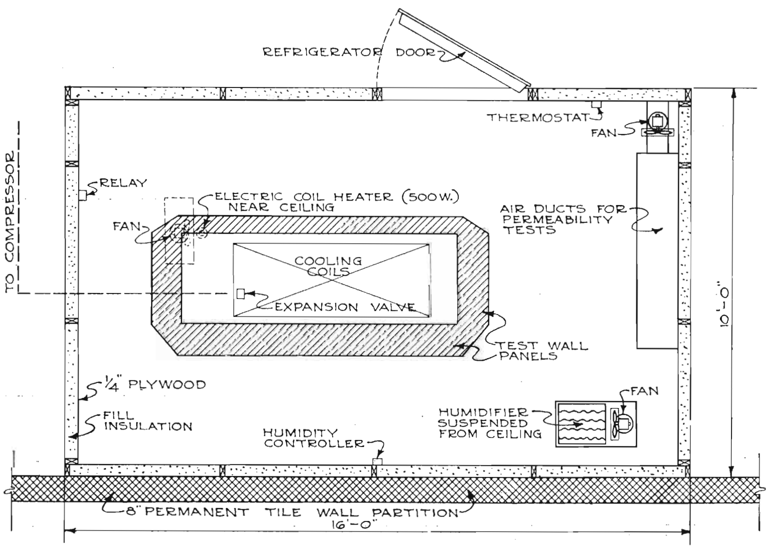


Fig. 10. Floor plan of constant temperature-humidity room and a view of part of the wall sections under test.

that the expanded vermiculite and rock wool are non-hygroscopic. Such materials as sawdust and stalks are relatively hygroscopic and have similar moisture content-relative humidity relationships as other hygroscopic materials.

TESTS ON WALL SECTIONS

CONSTANT TEMPERATURE-HUMIDITY ROOM

A well-insulated room (fig. 10) was constructed to make it possible to perform the experiments under controlled conditions. Heating and humidifying equipment with controls were provided to maintain a desired temperature and humidity. The walls of the room with overall dimensions of 10x16x8 ft., were constructed of 2x4-inch studs lined on both sides with ¼-inch plywood and insulated with ground cornstalks. The ceiling was formed by an overhead balcony which also was insulated in a manner similar to the walls.

The heat necessary to maintain a constant temperature within the room was supplied by a 500-watt electric coil heater placed near the ceiling and operated by a thermostat and relay. A fan running continuously placed directly behind the heater stirred the air within the room to give better uniformity of temperature.

The humidity within the room was maintained by circulating air over water and wetted toweling with an electric fan, the operation of which was controlled by a humidity controller. The location of this equipment within the room is shown in fig. 10. For maintaining cold temperatures on the cold side of the test walls a set of direct expansion cooling coils was used. The coils were cooled by a ⅓-ton methyl chloride Servel Compressor located outside of the room. The side of the test walls facing the coils and that exposed to the room correspond to the cold and warm sides of the test walls, respectively.

Inasmuch as no means of cooling and dehumidification were provided in the room, the loss of heat and water vapor to the coils within the test wall enclosure was sufficient so that no cooling or dehumidification was necessary to maintain the desired conditions. The control of conditions within the room was remarkably good. The temperature fluctuated rarely more than two degrees, and the relative humidity very seldom varied more than 3 percent, as revealed by a Frieze Hygrothermograph. The temperature over the cooling coils fluctuated from 6 to 8 degrees at intervals of about an hour. An occasional check on the relative humidity by the wet and dry bulb method and also with a hygrothermograph showed it to fluctuate a few percent about a mean of approximately 80 percent.

TABLE 4. MATERIALS AND TREATMENTS USED IN THE CONSTRUCTION OF THE TEST WALL SECTIONS.

Wa		Warm side of wall			Wall space	Cold side of wall		
Type	No.	C or U*	W.V.P.†	Description of materials and treatment	Insulation	C or U*	W.V.P.	Description of materials and treatment
Frame	F-1	3.00	12.8	1/4" D. F. plywood	Ground cornstalks	2.00	14.3	3/8" D. F. plywood
	F-2	.44	6.2	3/4" V. S. Celotex insulating sheathing	do.	do.	do.	do.
	F-3	High	11.0	Sheet metal with 18—1/16" holes	do.	do.	do.	do.
	F-4	3.00	1.8	1/4" D. F. plywood with Sisalkraft underneath	do.	do.	do.	do.
	F-5	.66	60.3	1/2" Homasote	do.	do.	do.	do.
	F-6	3.00	12.8	1/4" D. F. plywood	No insulation	do.	do.	do.
	F-7	do.	do.	do.	Ground cornstalks	.44	6.2	3/4" V. S. Celotex insulating sheathing
	F-8	do.	do.	do.	do.	High	11.0	Sheet metal with 18—1/16" holes
	F-9	do.	do.	do.	do.	2.00	1.8	3/8" D. F. plywood with Sisalkraft on outside
	F-10	do.	do.	do.	do.	.66	60.3	1/2" Homasote
	F-11	do.	do.	do.	Expanded vermiculite	2.00	14.3	3/8" D. F. plywood
	F-12	do.	do.	do.	Rock wool	do.	do.	do.
	F-13	2.50	9.0	3/4" plaster on wood lath	No insulation	.50	1.8	do. with cedar bevel siding and Sisalkraft between
	F-14	do.	do.	do.	Ground cornstalks	do.	1.8	do.
	F-15	3.00	12.8	1/4" D. F. plywood	do.	2.00		3/8" D. F. plywood with 6—1/2" holes
	F-16	do.	1.3	do. with two coats aluminum paint	D. F. sawdust	do.	14.3	3/8" D. F. plywood
	F-17	do.	12.8	1/4" D. F. plywood	do.	do.	do.	do.
	F-18	do.	do.	do.	Glass wool	do.	do.	do.
	F-19	High	0	Sheet metal	D. F. sawdust	High	High	Fine mesh screen
	F-20	do.	High	Fine mesh screen	do.	do.	do.	do.
	F-21	do.	do.	do.	do.	do.	0	Sheet metal

TABLE 4. MATERIALS AND TREATMENTS USED IN THE CONSTRUCTION OF THE TEST WALL SECTIONS.—(Continued)

Wall		Warm side of wall			Wall space	Cold side of wall		
Type	No.	C or U*	W.V.P.†	Description of materials and treatment	Insulation	C or U*	W.V.P.	Description of materials and treatment
	L–1			1 1/2'' concrete with two coats asphalt on inside of wall	No insulation			1 1/2'' concrete with two coats asphalt on inside of wall
	L–2			do.	Ground cornstalks			do.
Concrete	L–3			1 1/2'' concrete with two coats flat wall paint	do.			do.
L–Block	L–4			Same as L–1, with two coats al. pt. and flat wall paint	do.			do.
	L–5			3/4'' plaster on wood lath	do.			do.
	L–6			do. with two coats aluminum paint	do.			do.
	B–1			3/4'' plaster on wood lath	No insulation			4'' brick and sheathing of 3/8'' plywood with Sisalkraft
Brick veneer	B–2			do.	Ground cornstalks			do.
	B–3			do. with two coats aluminum paint	do.			do.
	T–1			4'' back-up tile with 1/2'' plaster	No insulation			4'' double-walled face tile, hard burned
Double tile wall	T–2			do.	Ground cornstalks			do.
	T–3			do. with two coats aluminum paint	do.			do.

*C and U are thermal conductance and transmittance, respectively, in B.t.u.'s/ft.^{2} hr. °F.
†W.V.P. is water vapor permeability in Gms /ft.^{2} Da. lb./in.^{2} vapor pressure difference.

METHOD

TYPES OF WALLS TESTED

The following types of walls were tested: (a) Frame, (b) brick veneer, (c) double-tile and (d) concrete L-block. Table 4 gives a tabulation of the description of materials, treatment and type of fill insulation used in each of the individual walls.

Since the frame walls could more readily be adapted to a wider variety of construction, a larger number of these were used to study the relation of water vapor permeability and thermal properties of both the warm and cold side of the walls to moisture accumulation. Wall F-1, which was constructed with $\frac{1}{4}$-inch plywood on the warm side and $\frac{3}{8}$-inch plywood on the cold side, was used for a basis of comparison. Any one of the other frame walls, excepting F-13 and F-14, differed from it only in some one respect. Hence, wall F-1 was used as a norm with which the results of the other walls were compared. The variations in the properties are indicated by the water vapor permeability and thermal conductance or transmittance given for each of these walls in the table.

The general plan for each of the other types of walls was to observe the relative differences in moisture accumulation between insulated and uninsulated walls and to observe the effect of the addition of a moisture barrier on the warm side of the wall.

CONSTRUCTION OF TEST WALLS

The size of test wall sections was governed primarily by available space, size of building units and ease of manipulation. The width of frame walls was the same as the distance between studs spaced 16 inches on centers, the height being somewhat greater than the width.

The essential construction details of each type of wall are given in fig. 11. The frame walls, when under test, were supported and held in place by a 2x6-inch wood frame, which permitted the removal of the walls for weighing without interfering with the test conditions. The other walls were enclosed in 2x10-inch wood frames, and a supporting frame was not used for these, inasmuch as there was no object in removing them to be weighed for detecting the amount of moisture in the wall.

The individual frames for the frame wall sections were made of 1x$3\frac{1}{2}$-inch white pine boards carefully matched to insure tightness at the corners and painted with two coats of aluminum paint before either the warm side panels or cold side panels were fastened to them. The edges and a margin of about $\frac{3}{4}$-inch of both the warm and cold side panels were covered with two coats

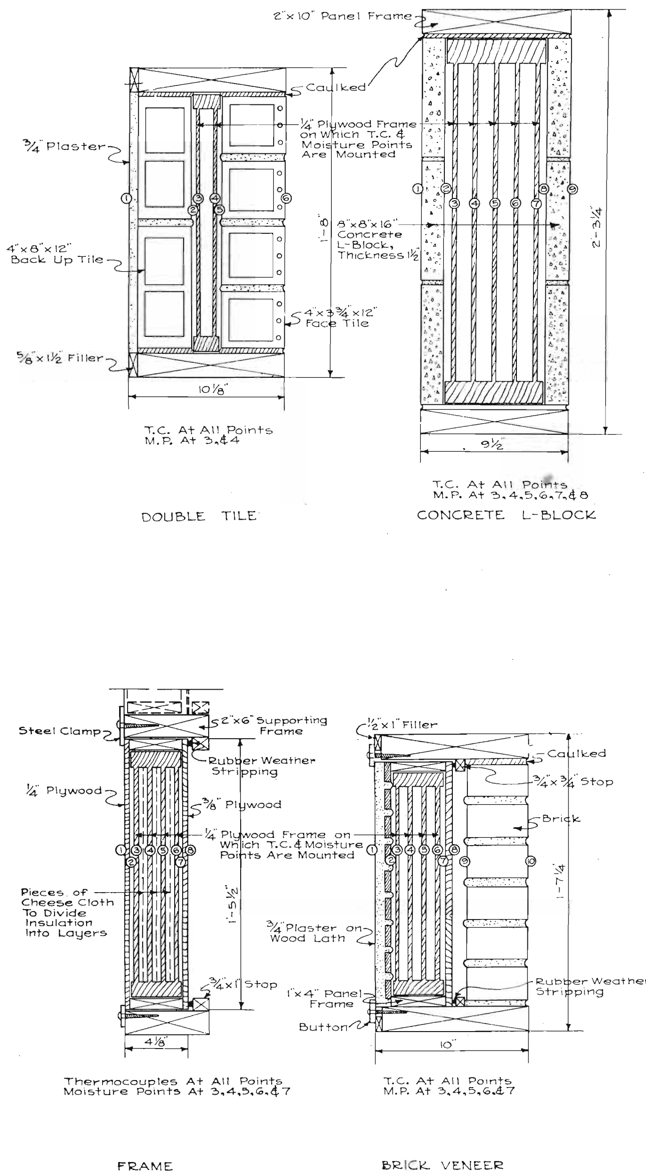


Fig. 11. Details of construction of test walls (the numbers indicate the points in the walls at which either thermocouples or moisture points were located).

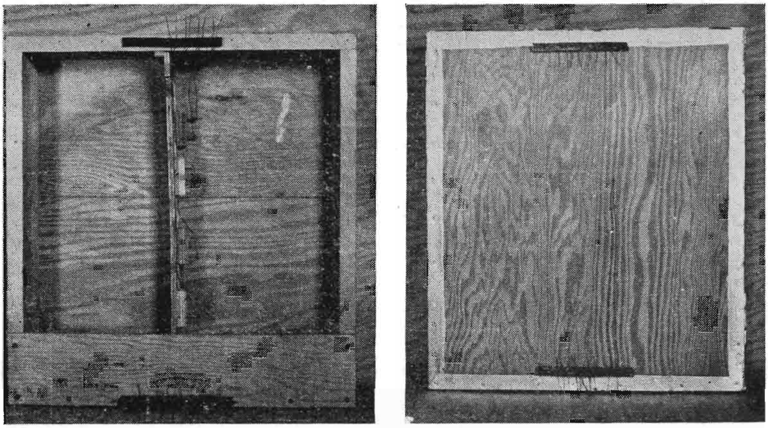


Fig. 12. Photos of sample frame walls similar to those used in the tests. (Left photo shows a cut-away section showing mounting of moisture points. Right photo shows a completed wall ready for test.)

of aluminum paint in case of the plywood panels, or in the case of those walls where fiber insulation boards were used, the edges and a ¾-inch margin were dipped in melted wax to insure against possibilities of edge leakage. The warm side panels were fastened permanently, but the cold side panels were made removable, since the outlet for the thermocouple and moisture point wires could be taken care of in a more satisfactory manner and because of the desirability of taking a photograph of the inside surface of this panel before the accumulated frost might melt, when the wall section was opened for observation at the end of the test period.

Within each wall in a vertical position was placed a light frame, made of ¼-inch plywood of the shape and size indicated in the detail drawings in fig. 14. These served as rigid mounting frames for the thermocouple junctions and wood moisture points for observing the temperature and moisture gradients within the wall space. The position of the frame and the manner in which the moisture points were mounted and staggered are shown in fig. 12.

In the frame walls which were insulated, the insulation was placed in four equal layers, separated by a single thickness of cheesecloth. The thermocouples and moisture points were placed in the center of each layer. The division of the insulation into layers by the use of cheesecloth eliminated the uncertainty as to the location of samples of insulation for moisture determinations.

The construction of the other walls in other respects was intended to be as nearly typical as possible. It was felt that the walls were of sufficient size to make observations at or near the center relatively free from possible edge effects.

All masonry units were laid up with mortar of the following proportions by weight: 1 part mortar mix, 4 parts cement and 7 parts fine sand. With the exception of the double-tile walls, all plaster was applied in three coats, in the following proportions: 1 part hair-fibered plaster and 2 parts fine sand for both the scratch and brown coats; $2\frac{1}{2}$ parts Regular Keene's Cement, and 1 part Finishing Hydrated Lime Putty for the finish coat. The plaster was applied in two coats in the tile walls.

The insulation was placed in from the top in the tile and con-

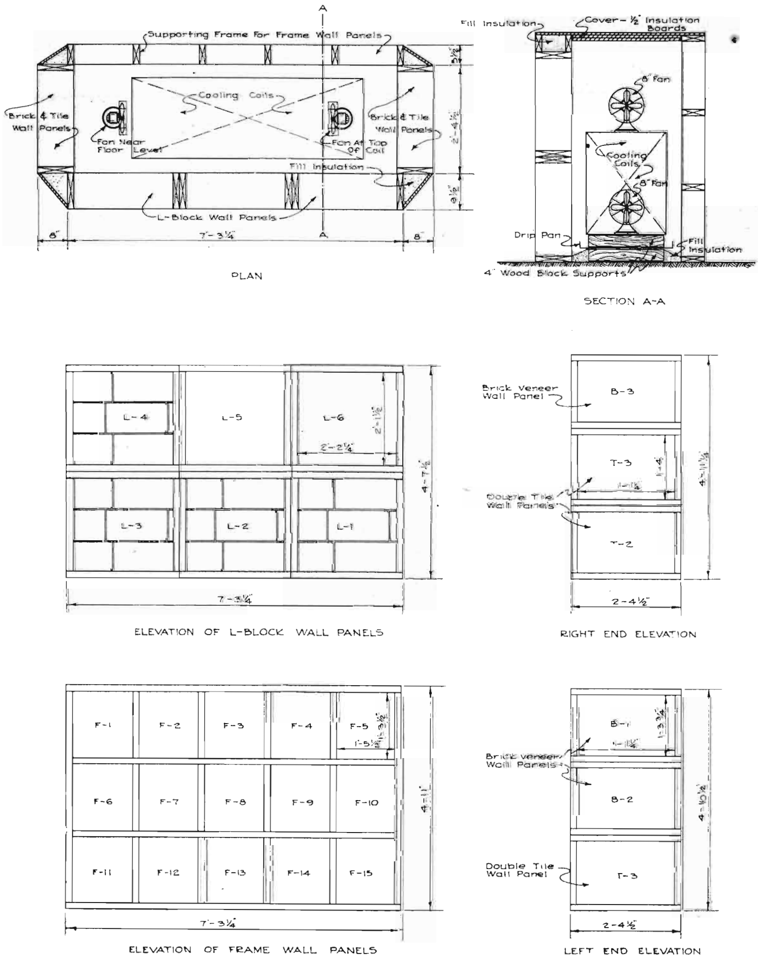


Fig. 13. Arrangement and location of test walls under test.

crete walls. No attempt was made in these walls to divide the insulation into layers as in the frame and brick veneer walls. Putty was used as a filler under the cover to prevent leakage.

The arrangement and location of the walls about the cooling coils are shown in fig 13. The sides of the walls facing the coils corresponded to the cold side of the wall.

WOOD MOISTURE POINTS

The wood moisture points, so-called because the moisture condition which they were to indicate within the wall space while the wall was under test, were made of ½x½x2-inch pieces of 5-ply Douglas Fir plywood. The moisture content of these wood pieces is indicated by the electrical resistance between two electrodes about 1¼ inches apart in the form of 2 tinned finishnails driven in the full thickness of the piece. In view of the large amount of lag and the influence of temperature on the resistance, little dependence was placed on them for determining quantitatively the moisture condition in the insulation as indicated by a Tag-Heppenstahl Wood Moisture Meter. They were of value, however, in indicating when conditions had reached a steady state or equilibrium. To be able to take account of variations in individual pieces of wood and the spacing of nails, each piece was calibrated at different relative humidities in the apparatus used for making the hygroscopicity determinations.

TEST CONDITIONS

The conditions maintained on the warm and cold sides of the walls were 75°F. and 50 percent relative humidity, and 12°F. and 80 percent relative humidity, respectively. The corresponding vapor pressures were .215 and .027 lbs./in.^{2}, which provided an overall vapor pressure difference of .188 lbs./in.^{2} across the wall. The temperature on the cold side fluctuated through a total range of 5 degrees. No attempt was made to control the relative humidity on the cold side of the wall. Measurements showed it to fluctuate a few percent with 80 percent as the probable mean.

Although it would have been desirable to have maintained lower temperatures on the cold side, there was a limitation with the type of refrigeration machine used to maintain a lower temperature with satisfactory operation. However, the conditions maintained were severe enough to observe the relative effects of the various factors considered in this study. The severity of the condition may also be increased by maintaining a higher vapor pressure on the warm side, which in this case is probably higher than ordinarily found.

TEST PROCEDURE

With the wall sections arranged in place as shown in fig. 13, the temperature on the cold side was brought to the desired level within a period of about 2 hours. The temperatures and resistances of the moisture points were read for all wall sections at intervals of 2 or 3 days. To determine the rate of moisture accumulation, the frame sections were removed and weighed at 2 or 3-day intervals.

At the end of the first test period for the frame walls and brick veneer walls, which varied in duration from 25 to 41 days, depending on the time of removal from test, the cold wall panels were removed, weighed and inspected and a photograph taken of the inside surface to show the moisture condition. In addition to samples of insulation taken from each layer, all parts of the wall were weighed to determine the moisture absorption in excess of what it had when it came to equilibrium with the conditions in the constant temperature-humidity room.

The second test period for walls F-16 to F-21, inclusive, varied from 20 to 29 days for the different walls. The observations on these were conducted in like manner as on the first group of frame walls.

The double-tile and concrete walls were left in place during both of the test periods referred to above, and therefore the test period for these was of 72 days duration. The final inspections on these were much more limited, since all sections had to be removed from test at the same time. Therefore, the final observations only included in addition to a visual inspection of the walls, the taking of a moisture sample from the region next to the warm and next to the cold side of the wall.

The moisture samples were dried from 5 to 6 hours at a temperature from 220° to 230°F.

RESULTS

TEST DATA

The data obtained from the tests on the wall sections are summarized in the accompanying tables 5, 6 and 7. These give the temperatures, moisture contents of the insulation and the relative and absolute vapor pressures at the designated locations in the wall. For the frame wall sections the total gain, rate of gain and the amount of excess moisture absorbed by the cold wall panels are given. The omissions of moisture content and vapor pressure data from these tables are due either to the fact that no moisture samples were taken or the wall was not insulated.

RELATION OF WATER VAPOR PERMEABILITY OF WARM AND COLD SIDES OF WALLS TO AMOUNT OF MOISTURE ACCUMULATION

Figure 14 shows the relation of the permeability of the warm and cold sides of the wall with the rate of moisture accumulation. The graphs show that the permeability of the warm side of the

TABLE 5. TEST DATA ON FRAME WALLS USED IN THE FIRST SERIES OF TESTS.

Wall no.		Location in wall										Duration of test	Total gain	Rate of gain	Moisture absorbed	
		Warm side	1	2	3	4	5	6	7	8	Cold side				Warm wall and frame	Cold wall
												(Da.)	(Gms.)	(Gms./Da. ft.²)	(Gms.)	(Gms.)
F-1	Temp. (°F)	75	73	71	64	51	39	26	18	15	12	33	96	1.66	12	26
	Moist. (%)				7.26	9.49	12.5	19.0								
	R.H. (%)	50			21	37	55	77	100		80					
	V.P. (lbs./in.²)	.215			.063	.068	.064	.044	.046		.027					
F-2	T	75	74	66	61	51	40	32	18	15	12	31	122	2.05	17	34
	M				7.15	8.75	10.6	21.9								
	R.H.	50			20	31	43	82	100		80					
	V.P.	.215			.053	.057	.052		.046		.027					
F-3	T	75	71	70	64	53	41	32	18	15	12	25	75	1.36	11	28
	M				6.66	9.55	12.0	19.7								
	R.H.	50			18	38	52	79	100		80					
	V.P.	.215			.052	.066	.066	.069	.046		.027					
F-4	T	75	73	71	65	53	41	31	18	15	12	30	69	.74	11	28
	M				7.45	9.50	11.4	18.4								
	R.H.	50			23	37	48	76	100		80					
	V.P.	.215			.069	.066	.061	.064	.046		.027					
F-5	T	75	73	68	62	51	38	26	18	15	12	28	264	6.29	12	37
	M				12.5	15.6	18.8	27.1								
	R.H.	50			62	71	78	88	100		80					
	V.P.	.215			.165	.131	.088	.059	.046		.027					
F-6	T	75	63	53	46	45	44	43	32	20	12	33	199	3.94	30	73
	M															
	R.H.	50									80					
	V.P.	.215									.027					
F-7	T	75	72	70	65	54	44	36	22	12	12	33	86	1.70	9	86
	M				8.40	10.5	13.0	16.7								
	R.H.	50			31	45	60	72	100		80					
	V.P.	.215			.092	.092	.084	.074	.057		.027					
F-8	T	75	72	70	63	51	40	30	22	17	12	33	107	1.76	11	7
	M				8.59	10.1	15.5	19.3								
	R.H.	50			32	42	68	78	100		80					
	V.P.	.215			.092	.078	.083	.063	.057		.027					

TABLE 5. TEST DATA ON FRAME WALLS USED IN THE FIRST SERIES OF TESTS.—(Continued)

Wall no.		Location in wall										Duration of test	Total gain	Rate of gain	Moisture absorbed	
		Warm side	1	2	3	4	5	6	7	8	Cold side				Warm wall and frame	Cold wall
												(Gms.)	(Gms.)	(Gms./Da. ft.^{2})	(Gms.)	(Gms.)
F-9	T	75	72	70	64	52	40	30	18	14	12					
	M				9.55	11.6	14.3	22.4								
	R.H.	50			40	52	65	83	100		80	41	121	1.72	5	44
	V.P.	.215			.118	.100	.079	.067	.046		.027					
F-10	T	75	72	70	64	53	41	29	21	15	12					
	M				8.20	9.78	12.7	19.6								
	R.H.	50			29	40	57	78	100		80	30	26	.29	–4	29
	V.P.	.215			.085	.077	.072	.060	.053		.027					
F-11	T	75	70	67	61	50	37	27	18	14	12					
	M				.49	.53	.29	11.1								
	R.H.	50									80	34	110	1.81	13	33
	V.P.	.215									.027					
F-12	T	75	72	70	64	52	39	27	15	12	12					
	M				.23	.27	0	6.4								
	R.H.	50									80	34	98	1.41	5	32
	V.P.	.215									.027					
F-13	T	75	64	55	50	49	48	47	40	16	12					
	M															
	R.H.	50									80	34	126	1.99	5	58
	V.P.	.215									.027					
F-14	T	75	70	67	61	50	38	27	21	13	12					
	M				11.8	14.4	18.7	36.2								
	R.H.	50			55	66	77		100		80	41	159	2.26	–5	63
	V.P.	.215			.146	.118	.087		.053		.027					
F-15	T	75	71	69	61	50	39	30	18	15	12					
	M				8.73	10.8	14.6	18.8								
	R.H.	50			33	47	66	77	100		80	34	91	1.52	–6	33
	V.P.	.215			.086	.084	.078	.064	.046		.027					

TABLE 6. TEST DATA ON FRAME WALLS USED IN THE SECOND SERIES OF TESTS.

Wall no.		Location in wall													Duration of test	Total gain	Rate of gain	Moisture absorbed	
		Warm side	1	2	3	4	5	6	7	8	9	10	11	Cold side				Warm wall and frame	Cold wall
															(Da.)	(Gms.)	(Gms./Da. ft.^{2})	(Gms.)	(Gms.)
F–16	Temp. (°F)	75	72	70	66	59	52	45	38	32	24	19	16	14					
	Moist. (%)				5.38	6.30	7.56	9.00	10.2	12.3	17.3	73.6							
	R.H. (%)	50			21	27	37	47	59	70	84	100			29 1/2	21	.39	–6	42
	V.P. (lbs./in.^{2})	.215			.066	.066	.071	.069	.068	.060	.053	.048		.036					
F–17	T	75	72	70	67	59	51	44	37	30	22	18	15	14					
	M				6.08	6.94	8.22	9.59	10.9	12.5	17.2	238							
	R.H.	50			26	34	44	53	62	70	84	100			29	77	1.74	26	61
	V.P.	.215			.084	.085	.082	.076	.067	.058	.050	.046		.036					
F–18	T	75	72	70	67	60	50	46	38	31	24	18	15	13					
	M				0						35								
	R.H.	50													29	70	1.14	9	42
	V.P.	.215												.036					
F–19	T	75	66	66	63	57	51	45	39	33	27		18	16					
	M				4.51	5.32	6.39	7.62	8.60	9.59	12.0								
	R.H.	50			15	18	25	33	44	55	67			80	20	–8	0	17	—
	V.P.	.215			.042	.042	.046	.049	.051	.051	.047			.036					
F–20	T	75	66		63	54	48	39	32	27	21	14	13	13					
	M				12.0	13.8	15.2	16.9	18.3	21.4	17.4								
	R.H.	50			74	80	82	85	87	88	84		90		27	92	.88	32	—
	V.P.	.215			.211	.178	.136	.107	.082	.062	.044		.036	.036					
F–21	T	75	66		64	56	46	39	32	28	26	22	20	16					
	M				11.9	13.8	16.0	19.6	23.7	40.9	138	158	402						
	R.H.	50			74	80	84	91	98	100	100	100	100	80	29	653	27.0	33	—
	V.P.	.215			.218	.178	.134	.108	.087	.075	.067			.036					

TABLE 7. TEST DATA ON BRICK VENEER, DOUBLE-TILE AND CONCRETE L-BLOCK WALLS.

L–BLOCK WALLS

Wall no.		Location in wall											Duration of test (Da.)
		Warm side	1	2	3	4	5	6	7	8	9	Cold side	
L–1	Temp. (°F)	75	59	55	46	44	43	42	41	28	22	12	72
	Moist. (%)	Layer of ice on inside of cold wall											
	R.H. (%)	50								100		80	
	V.P. (lbs./in.²)	.215										.027	
L–2	T	75	66	65	61	52	43	35	26	20	18	12	72
	M				11.3					69.3			
	R.H.	50			52					100		80	
	V.P.	.215			.135					.050		.027	
L–3	T	75	67	66	62	53	45	36	28	20	18	12	72
	M				9.6			14.7		119			
	R.H.	50			40			66		100		80	
	V.P.	.215			.110			0.69		.050		.027	
L–4	T	75	70	68	64	55	47	38	29	22	20	12	72
	M				8.69		11.9			50.1			
	R.H.	50			34		53			100		80	
	V.P.	.215			.10		.084			.056		.027	
L–5	T	75	73	71	64	54	44	35	25	18	17	12	72
	M				10.8					135			
	R.H.	50			50					100		80	
	V.P.	.215			.147					.046		.027	
L–6	T	75	72	70	63	54	44	35	27	19	18	12	72
	M				8.06					31.2			
	R.H.	50			27					100		80	
	V.P.	.215			.078					.048		.027	

DOUBLE-TILE WALLS

Wall no.		Location in wall								Duration of test (Da.)
		Warm side	1	2	3	4	5	6	Cold side	
T–1	T	75	62	48	43	40	35	20	12	72
	M	Moisture on inside of cold wall								
	R.H.	50							80	
	V.P.	.215							.027	
T–2	T	75	71	63	56	37	19	13	12	72
	M				10.5		42.1			
	R.H.	50			45		100		80	
	V.P.	.215			.100		.048		.027	
T–3	T	75	70	62	53	36	19	13	12	72
	M				11.5		27.5			
	R.H.	50			52		100		80	
	V.P.	.215			.103		.048		.027	

TABLE 7. TEST DATA ON BRICK VENEER, DOUBLE-TILE AND CONCRETE L-BLOCK WALLS.—(Continued)

BRICK VENEER WALLS

Wall no.		Location in wall: Warm side	1	2	3	4	5	6	7	8	9	10	Cold side	Duration of test (Da.)
B-1	T	75	68	61	58	57	57	56	50	40	28	18	12	41
	M	Lower part of sheathing 53% moist												
	R.H.	50							100				80	
	V.P.	.215							.178				.027	
B-2	T	75	72	70	66	57	46	37	30	24	19	15	12	41
	M				10.9	13.4	16.4	22.5						
	R.H.	50			51	64	72	84	100				80	
	V.P.	.215			.166	.157	.124	.099	.081				.027	
B-3	T	75	73	71	67	59	49	40	30	27	21	18	12	41
	M				7.28	11.0	13.0	19.5	32.6					
	R.H.	50			27	50	60	79					80	
	V.P.	.215			.088	.122	.104	.094					.027	

wall influences the rate of accumulation much more than that of the cold side. Wall F-5 which had a high permeability of 60 gms./ft.^{2} Da. lb./in.^{2} vapor pressure difference on the warm side gained moisture at the rate of 6.29 gms./ft.^{2} Da. Wall F-10, with the same permeability on the cold side, gained only at the rate of .29 gms./ft.^{2} Da. Each wall gained moisture with the exception of F-19, which had sheet metal on the warm side and fine mesh screen on the cold side. It actually lost 8 grams of moisture

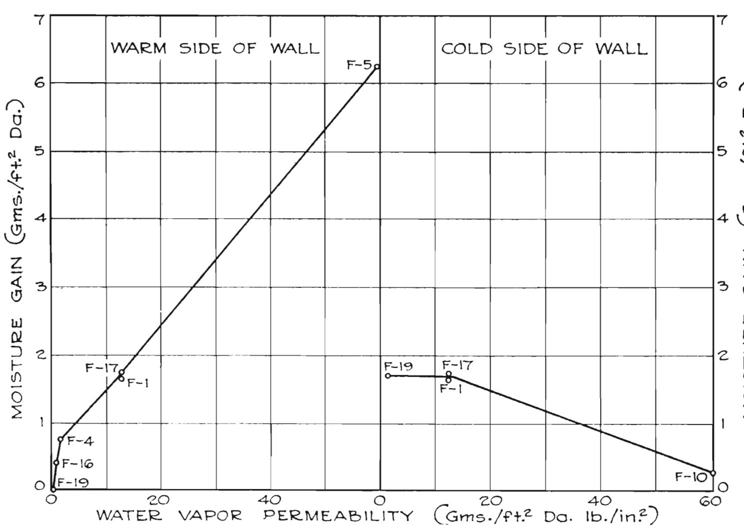


Fig. 14. Variation of rate of moisture gain of frame walls with the water vapor permeability of warm and cold sides of the wall.

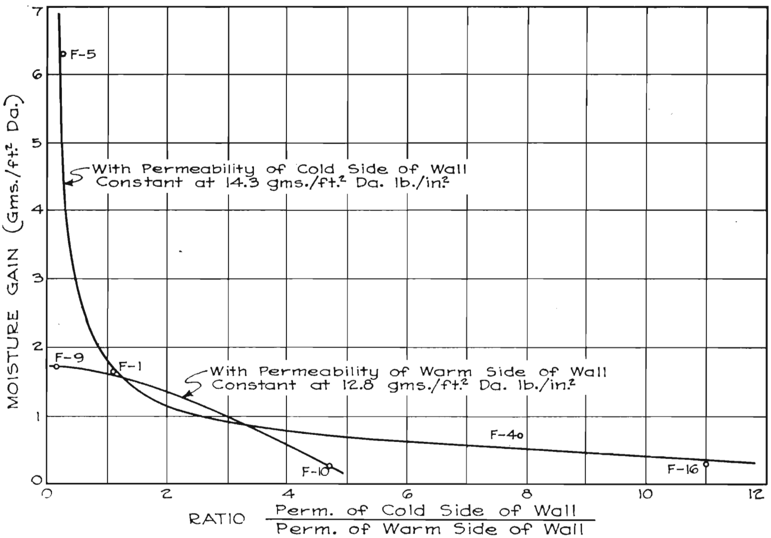


Fig. 15. Variation of rate of moisture gain of frame walls with the ratio of water vapor permeability of cold side to that of warm side of wall.

during the first part of the test period. Even walls F-4 and F-16 with moisture barriers on the warm side accumulated moisture.

The above data appear to indicate that the rate of accumulation does not depend altogether on the permeability of either side of the wall but rather on the ratios of the permeabilities of the two sides of the respective walls. Figure 15 shows the variation of the rate of gain with the ratio of the permeability of the cold to that of the warm side of the wall. It will be noted that the ratio of the permeabilities must be well above 12 to prevent moisture accumulation for the conditions under which these walls were tested. One should note further, that by increasing the permeability of the cold side of the wall, the ratio need not be as large to obtain the same reduction in rate of accumulation or to prevent it completely.

However, it should be pointed out that the low rate of gain for wall F-10 was in part due to a higher surface temperature on the inside of the cold wall. Its temperature at this point, 21°F. as compared to 18°F. of walls F-1 and F-9, provided a greater vapor pressure differential across the cold side of the wall. It had a difference of .026 lbs./in.^{2} as compared to .019 lbs./in.^{2} for the other two walls. Consequently the moisture transmitted through the cold side of the wall was greater in proportion by the ratio of these pressures. If a corresponding correction were applied, its rate of gain would be .56 gms./ft.^{2} Da. instead of .29 gms./ft.^{2} Da. This value, when plotted on the graph, would place it near the upper curve.

It follows from a consideration of equation (e) that the ratio required for zero accumulation may be less by the ratio of the permeability of the cold side of the wall to that of the fill insulation (K_c/K_b), which in this case is 60/76 or about 1. This is in good agreement with the equation just referred to.

It is of interest to note the rate of gain of walls F-20 and F-21 which represent extremes in permeabilities. Wall F-21 with a screen on the warm side and sheet metal on the cold side gained over 653 grams moisture during the period under test of 29 days. The rate of gain was 27 gms./ft.^{2} Da. in contrast to wall F-19 with no gain. Wall F-20 with both of its walls of fine mesh screen gained only at the rate of .88 gms./ft.^{2} Da. toward the end of the test period. There was some doubt as to whether this wall would have finally ceased to gain if left on test indefinitely.

RELATION OF THE WATER VAPOR PERMEABILITY OF WALLS TO MOISTURE DISTRIBUTION AND VAPOR PRESSURE GRADIENTS

As shown in fig. 1, the relative humidity or relative vapor pressure varies within the wall space according to the existing actual vapor pressures and temperatures. Consequently, in a wall filled with hygroscopic insulation, the moisture will be so distributed in the insulation that at every point the latter will be in equilibrium with the vapor pressures at corresponding points.

The redistribution of moisture in the insulation was evident during the first several days of the test period, as revealed by the readings of the wood moisture points. The points next to the warm wall dried, while those next to the cold side increased in moisture content.

CALCULATION OF VAPOR PRESSURES WITHIN THE WALL SPACE

It follows from the preceding paragraphs, that it is possible to determine relative and actual vapor pressures from the moisture content of the insulation providing the latter is relatively hygroscopic. For those walls which were insulated with either sawdust or ground cornstalks, the relative vapor pressures were determined from the equilibrium moisture content data given in fig. 9. In order to approximate the true values as closely as possible, corrections for the effect of temperature on the equilibrium moisture content were applied, since the various layers of insulation are all at different temperatures. Inasmuch as the effect of temperature was not determined in the hygroscopicity measurements of these insulants, corrections similar to those available for wood (14) were applied.

An opportunity to check the reliability of these calculations is presented by wall F-19 (see fig. 16), in which the actual vapor pressure throughout the entire wall is the same as that on the cold side, because of the zero permeability of the warm side of the wall and zero vapor resistance of the cold side of the wall. Although the results appear somewhat erratic, the range of the extreme values is only a small fraction of the total difference in pressures across the wall. Discrepancies such as lower actual vapor pressures near the warm side of the wall than those in the colder parts, which is contrary to theory, have been noted in a few walls, in particular F-16 and F-17. These discrepancies are considered to be due largely to the lack of proper temperature corrections.

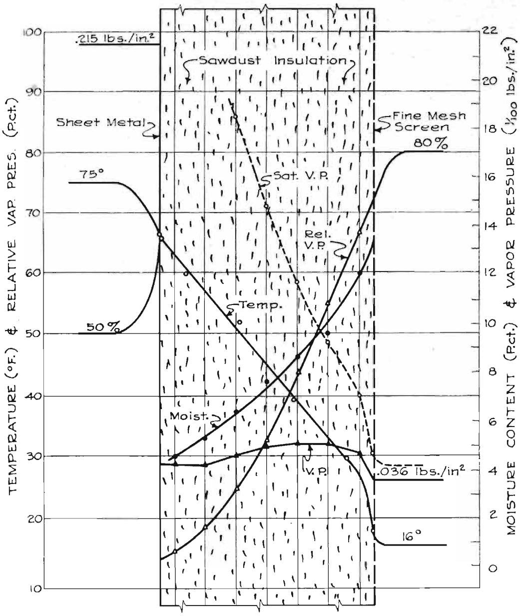
The vapor pressure gradient at saturation corresponds to the temperatures shown by the temperature gradient. It is presented to show the degree to which the actual vapor pressures approach those at saturation in the various parts of the wall.

OBSERVATIONS WITH SPECIAL WALLS

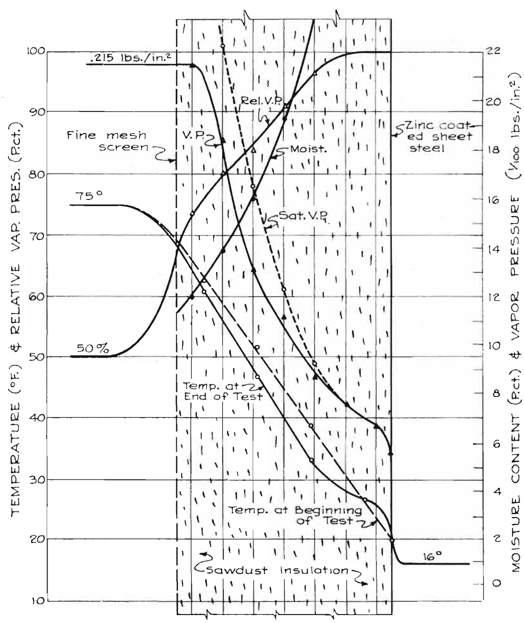
Walls F-19, F-20 and F-21 which were constructed to give extremes in permeabilities of warm and cold sides of the walls were excellent for observing the variation in distribution of moisture and vapor pressure gradients. These were insulated with fine Douglas Fir sawdust which was divided into seven layers instead of four to give greater reliability on the determination of the moisture gradient through the insulation. The temperature, relative and absolute vapor pressures for these walls at the end of the test period are shown in table 6 and figs. 16 and 17.

The effect of extreme vapor resistance in either the warm or cold side of a wall on the distribution of the moisture are shown by the observations with these walls. In wall F-19, with zero permeability on the warm side, the insulation next to the warm side dried from a moisture content of 8 to 4.51 percent, and it gained up to 12 percent on the cold side. Wall F-21, which is just the other extreme, had moisture contents much higher, as would be expected. These varied from 12 percent on the warm side to over 100 percent within an inch from the wall. It was still higher where the insulation was in contact with the cold wall. A layer of sawdust ¾-inch in thickness next to the cold wall had frozen into a solid mass. This amount of moisture changed the thermal characteristics of the wall as shown by the location and shape of the temperature gradients at the beginning and end of the test.

Since these walls represent extremes in combinations of water vapor permeabilities of the two sides of the wall, the vapor pressure gradients are also extremes for the conditions of tempera-



F-19.



F-21.

Fig. 16. Temperature, moisture content and vapor pressure gradients in walls F-19 and F-21.

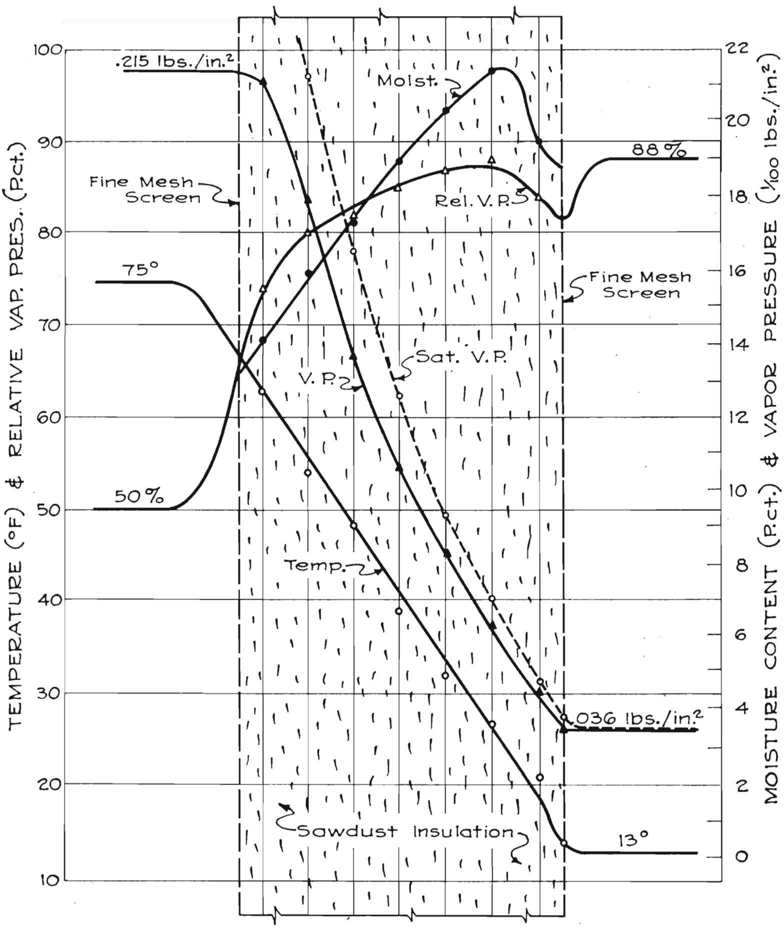


Fig. 17. Temperature, moisture content and vapor pressure gradients in wall F-20.

ture and humidity to which the walls were subjected. In wall F-19, the pressures are about the same as those on the cold side of the wall, whereas in wall F-21, it drops from .215 lbs./in.² on the warm side of the wall to .057 lbs./in.² on the cold side. Walls with any other combinations of permeabilities of cold and warm sides of walls would have vapor pressure gradients which would lie between these two extremes.

The degree to which the actual vapor pressures approach those at saturation at corresponding points is shown not only by the relative humidities but also by the differences in their values. In wall F-19, the differences are large throughout the wall, whereas in wall F-21, they coincide near the cold side of the wall, and the differences are also much less in the regions near the warm side of the wall.

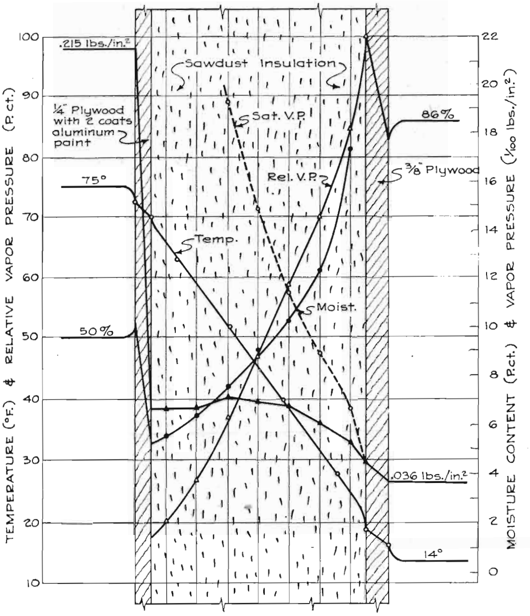
Wall F-20 (fig. 17), with screens on both sides of the wall, had practically the same vapor pressure characteristics as wall F-21. Undoubtedly just as much or more water vapor flowed into this wall as in wall F-21, but it was permitted to pass on through the cold side. The moisture content of the insulation next to the warm side was nearly the same. The fact that the moisture content was less in the outer layer than the adjacent layers was due, very likely, to the lower relative humidity in the region near the cold wall. As may be noted, the moisture content in any of the layers was not extremely high, since the relative humidity did not exceed 90 percent.

These results appear to indicate that a wall of sawdust of very low permeability will accumulate moisture to bring the insulation to equilibrium with the relative humidity within the wall, retaining very little, if any, free moisture. The placing of a material, with less permeability per unit of thickness than that of the insulation, on the cold side of the wall would no doubt result in excess moisture being retained in the wall.

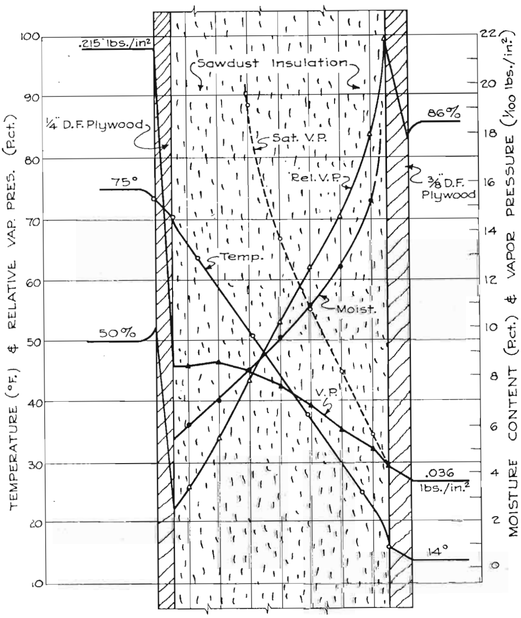
The data for the conditions in the walls of F-16 and F-17 are also shown in fig. 18. In these it may be noted that the moisture content, relative humidity and vapor pressures increased when the ratio of the permeability of the cold side, to that of the warm side, was lower.

Wherever there was an accumulation of moisture, the concentration of the moisture was always at the boundary between the insulation and the cold side of the wall. The accumulation of moisture on the inside of the cold side of walls F-5 and F-10 are shown in the photos of fig. 19. Since the cold sides of walls were in direct contact with free water or ice, it naturally follows that these absorbed a good deal of moisture. Tables 5 and 6 show the amounts of moisture absorbed by the cold sides of the wall in excess of the equilibrium moisture content at 50 percent relative humidity.

The greater slope in the vapor pressure gradients in the colder part of walls F-16 and F-17 (fig. 18) is undoubtedly due to temperature, since the drop in pressure across the insulation due to the flow would be uniform, i.e., the vapor pressure gradient across the insulation would be a straight line. There is, therefore, some evidence of the additional drop in pressure in the colder part of the insulation due to temperature, which was discussed above in the analysis of moisture accumulation.



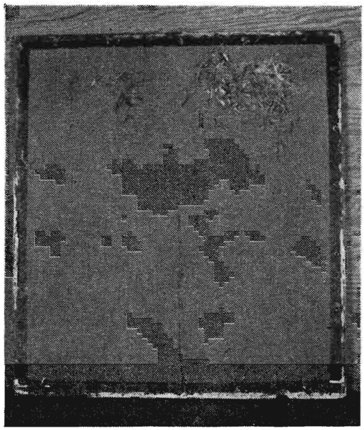
F.16.



F-17.

Fig. 18. Temperature, moisture content and vapor pressure gradients in walls F-16 and F-17.

Wall F-5.



Wall F-10.

Fig. 19. Condition of inside of cold side of walls F-5 and F-10. Note the concentration of ice on portion of a layer of insulation folded back in wall F-5 as contrasted with only a trace of ice on the upper part of wall F-10.

OBSERVATIONS WITH WALLS OF CONVENTIONAL CONSTRUCTION

Similar distribution of moisture within the insulation was observed with the frame, brick veneer, double-tile and concrete L-block walls, as in the special walls. In addition to the condensation of moisture occurring at the boundary between the insulation and the cold side of the wall, there was also some condensed moisture between the plywood sheathing and the kraft paper in walls B-1, B-2, F-13 and F-14. This shows that for materials with the same thermal properties, moisture may condense at the boundaries between materials of different permeabilities providing the one of lower permeability is placed to the cold side of the other.

In the same type of walls, the effect of a moisture barrier on the warm side of the wall produced lower moisture contents in the insulation throughout the wall than those without such a barrier, although there was some condensate at the boundary of the insulation and the cold side of the wall. This effect may be noted by making comparisons of the following pairs of walls (see table 7); L-3 and L-4, L-5 and L-6, T-2 and T-3, and B-2 and B-3.

The fact that there is an accumulation of moisture in the form of condensation in wall L-6, for example, does not necessarily mean that this moisture permeated through the warm side of the wall. Even with zero permeability, i.e., a perfect moisture barrier, of the warm side of the wall, it is easily possible, with an hygroscopic insulation such as ground stalks, to have a redistri-

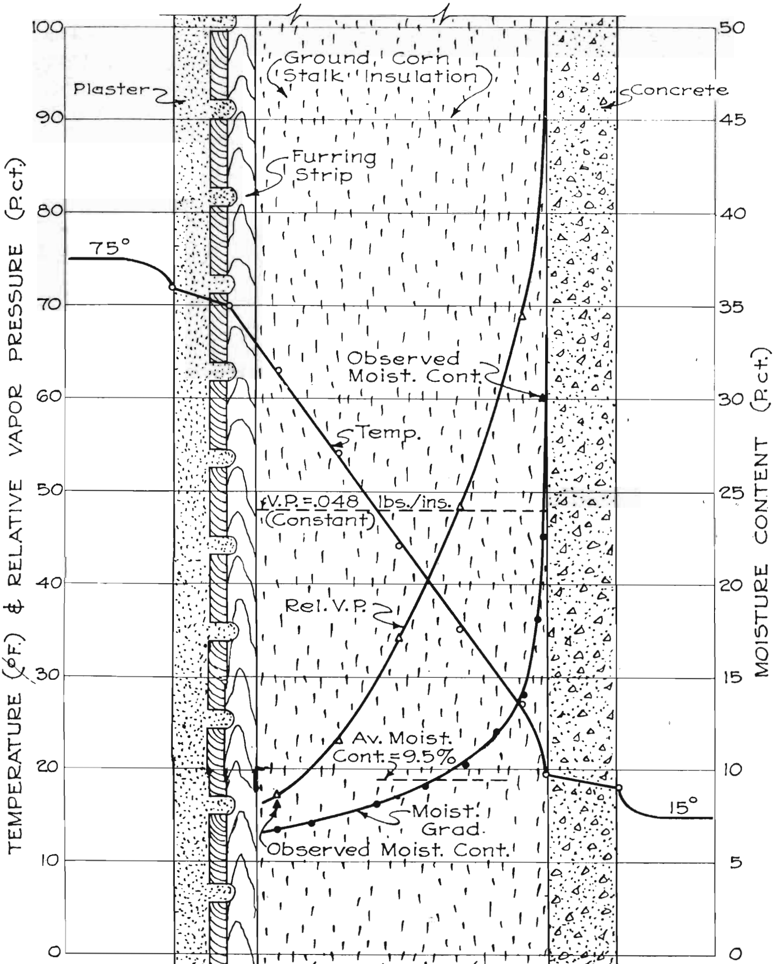


Fig. 20. Calculated moisture gradient in wall L-6 with an actual vapor pressure of .048 lbs./in.² assumed to be constant throughout the insulation. The observed moisture contents next to the warm and cold sides of the wall are also shown.

bution of the moisture in the insulation with free moisture resulting in the insulation next to the cold wall, providing there is sufficient moisture in the insulation originally. By reference to tables 2 and 4, it is noted that wall F-6 had zero permeability, yet some condensation of moisture next to the cold wall was observed.

It can be shown readily in the case of wall L-6, for example, at what average moisture content of the ground, cornstalk insulation condensation will take place. Figure 20 shows a section of this wall with the temperature gradient across the wall as observed under test. With zero permeability of the warm side of the wall, the actual vapor pressure will be constant and will be just equal to the saturation pressure corresponding to the temperature of the inside wall. Hence, the equilibrium moisture content of the insulation at various points can be calculated from the prevailing relative vapor pressures, which were determined from the ratio of the actual vapor pressure to the saturation vapor pressure corresponding to the temperature. The moisture gradient together with the relative vapor pressure gradient are shown. It will be noted that the moisture gradient is very steep next to the cold wall, which is due to the increase in slope of the relative vapor pressure gradient in the vicinity of the cold wall. By determining the area under the moisture gradient, the average ordinate or moisture content was found to be 9.55 percent. Hence, any moisture in excess of this amount would appear as condensate on the surface of the cold wall.

RELATION OF THERMAL CONDUCTIVITY OF WARM AND COLD SIDES OF WALLS TO MOISTURE ACCUMULATION

The results on the relation of the thermal resistance of the warm and cold sides of the walls to moisture accumulation are given by walls F-2, F-3, F-7, F-8 and F-1 in table 5. Although the results show tendencies as expected, they are not strictly comparable because of the difficulty in obtaining materials of widely varying thermal resistances which would have the same vapor resistance. For example, the sheet iron with 1/16-inch holes and the ¾-inch moisture proofed sheathing which was used on the warm sides of walls F-2 and F-3 and the cold sides of walls F-7 and F-8 showed water vapor permeabilities on the order of about one-half that of the ¼-inch D. F. plywood as determined by method A.

The thermal properties of both sides of the wall are important, insofar as the temperature of the inside of the cold side of the wall is influenced. As shown on p. 554, the small amount of moisture accumulation of wall F-10 was due in part to the high thermal resistance of the cold side of the wall.

RELATION OF HYGROSCOPICITY OF INSULATION TO MOISTURE ACCUMULATION

The variation of the rate of gain of moisture of walls which were insulated with different kinds of insulating materials are presented in fig. 21. Walls F-1, F-11 and F-17, insulated with ground cornstalks, expanded vermiculite and sawdust, respectively, gained moisture at about the same rate. Walls F-12 and F-18, with rock wool and glass wool, respectively, gained

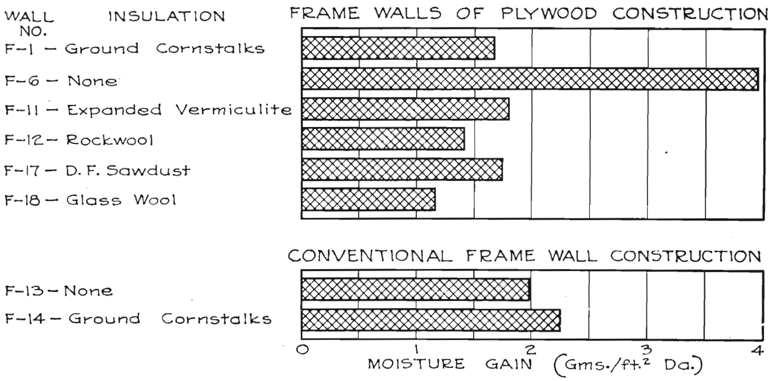
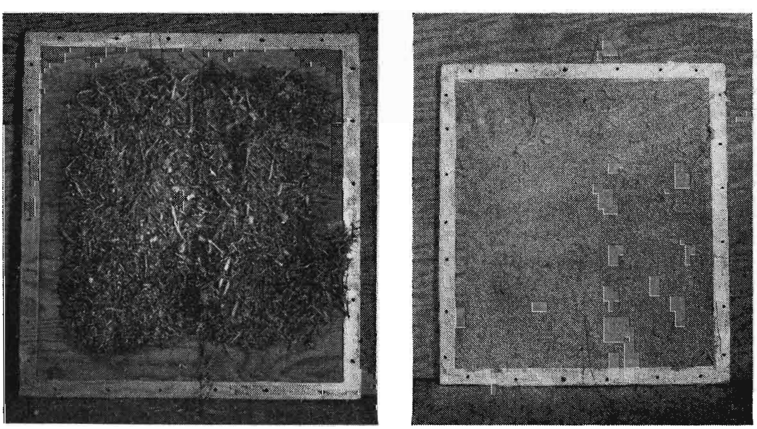


Fig. 21. Rate of moisture gain of uninsulated and insulated walls with different kinds of fill insulation.

somewhat less rapidly. This difference may be attributed to the lower permeability of the rock wool as compared with either the ground cornstalks or the sawdust, as revealed by the permeability tests. (See table 2.) The conditions on the inside of the cold side of the wall for walls F-1, F-17, F-12 and F-11 are shown in figs. 22 and 23. It is questionable that in view of these results that the hygroscopicity of the insulation has an appreciable effect if any on the rate of condensation of moisture within a wall.

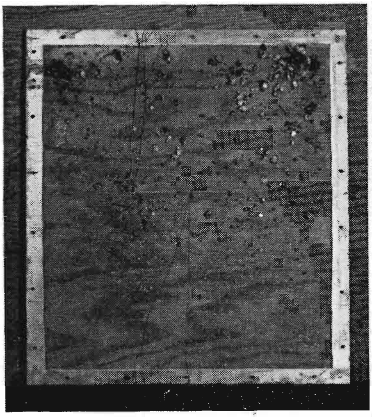
COMPARISON OF INSULATED AND UNINSULATED WALLS

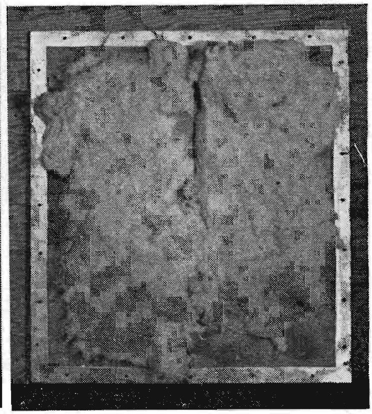
Figure 24 shows that the uninsulated frame walls of plywood



Wall F-1. Ground cornstalks. **Wall F-17. D. F. sawdust.**

Fig. 22. Condition of inside of cold side of walls F-1 and F-17.



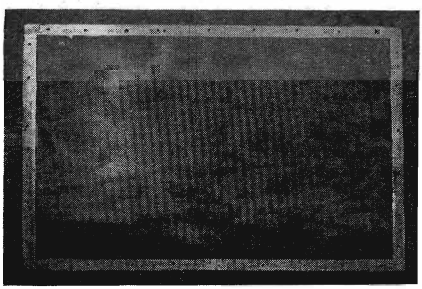


Wall F-11. Expanded vermiculite. **Wall F-12. Rock wool.**

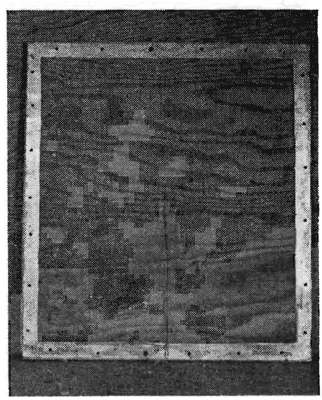
Fig. 23. Condition of inside of cold side of walls F-11 and F-12. About the same amount of ice was observed in wall F-12 as in F-11.

construction accumulated moisture over twice as fast as those which were insulated. However, in the conventional frame wall construction, the insulated wall gained at a slightly greater rate.

The moisture which condenses in an uninsulated wall is concentrated at the bottom portion of the inside of the cold wall. It therefore may be more hazardous than if it were distributed as in the case of an insulated wall. For example, in the case of the uninsulated brick veneer wall, B-1, the sheathing had become very wet (fig. 24) and even molded along its lower portion. Samples cut from this area showed a moisture content of over 50 percent.



Wall B-1.



Wall F-6.

Fig. 24. Condition of inside of cold side of uninsulated walls B-1 and F-6 (note layer of ice on F-6 and molded condition of B-1).

The uninsulated concrete block wall L-1 had a layer of ice of about ¼-inch thick on the inside surface of the cold wall. The uninsulated double tile wall T-1 showed dampness only in places.

DISCUSSION OF RESULTS OF TESTS ON WALL SECTIONS

The results of tests on the wall sections demonstrate the important principle, that unless the warm side of the wall is impermeable to water vapor, the permeability of the cold side of the wall must be many times that of the warm side to prevent moisture from accumulating within the wall. Walls F-10 and F-16 which had high ratios of permeabilities reduced the rate of moisture accumulation considerably but not completely. An increase in the ratio in both walls would undoubtedly have resulted in the prevention of accumulation entirely as may be noted from fig. 19 and table 8, a discussion of which is given below. The venting of the cold side of wall F-15 to the cold air by means of six ½-inch holes was not effective, since it gained moisture nearly as rapidly as wall F-1 without holes.

The extent to which the results agree with the analysis of moisture accumulation is shown in table 8. The observed and calculated rates of moisture gain, and the minimum calculated ratios of the permeabilities of the cold to those of the warm sides of the walls to prevent moisture accumulation are given.

The calculated values for both the rate of moisture accumulation (M_a) and the minimum ratio (K_c/K'_a) of the water vapor per-

TABLE 8. OBSERVED AND CALCULATED MOISTURE GAINS, AND ACTUAL AND CALCULATED MINIMUM RATIOS OF PERMEABILITIES.

Wall no.	Vapor pressures (lbs./in.^{2})			Moisture gain (M_a) (Gms./ft.^{2} Da.)		Ratio of permeabilities K_c/K'_a	
	P_a	P'_c	P_d	Observed	Calculated	Actual	Calculated* minimum
F–1	.215	.046	.027	1.66	1.59	1.23	8.7
F–4	.215	.046	.027	.74	.03	7.9	8.7
F–5	.215	.046	.027	6.29	5.41	.24	8.7
F–9	.215	.046	.027	1.72	1.83	.14	8.9
F–10	.215	.053	.027	.29	.21	4.7	5.4
F–16	.215	.048	.036	.39	.04	11.0	13.8
F–17	.215	.046	.036	1.74	1.63	1.23	16.7

*Calculated minimum ratio to prevent moisture accumulation.

meability of the cold side of the wall to that of the warm side to prevent moisture accumulation, were determined from equations (d) and (e) respectively (see page 523). The values for the water vapor permeabilities were taken from table 4, and the observed vapor pressures P_a, P'_c and P_d were taken from tables 5 and 6. The notation in table 8 corresponds to that of the above equations.

With the exception of walls F-4 and F-16, the calculated rates of accumulation are in fair agreement with the observed results. The calculated rates for the entire group are lower, as a whole, than the observed values, which may be accounted for in part at least by the absorption of moisture by the cold sides of the walls from the cold air at a relative humidity of 80 percent.

The calculated ratios show also that the ratios of the permeabilities of walls F-4, F-10 and F-16 were not high enough to prevent accumulation. It should be pointed out, however, that in the calculation of these ratios the difference $P'_c - P_d$ is very small. Hence, a small variation in the observation of these pressures would change the ratios appreciably. The higher pressures P_d for walls F-16 and 17 are due to the higher temperature on the cold side during the second series of tests.

Although the methods used in making observations on the wall sections as a whole were satisfactory, the determinations of the relative and absolute vapor pressures from the moisture content of the insulation were erratic in some cases. Wall F-19 (fig. 20) offered a good opportunity to check the degree to which the observed pressures agreed with theory, since the vapor pressures throughout the wall should all be the same as that on the cold side. The deviations, which are only a small part of the total vapor pressure difference, are probably due to the fact that the equilibrium condition had not been reached, and also probably to the lack of the proper temperature correction for the equilibrium relative vapor pressure of the fill insulation.

CONCLUSIONS

1. The factors which influence the condensation of moisture in walls are:
   a. Temperatures and vapor pressures on both sides of the wall.
   b. Water vapor permeability of the warm and cold sides of the wall.
   c. Thermal properties of the component parts of the wall.
2. The necessary condition for condensation of moisture to take place within a wall subjected to a temperature difference is that the temperature at some point in the wall must be below the dew point of the air on the warm side of the wall.
3. The rate of moisture accumulation in a wall increases with the water vapor permeability of the warm side of the wall and decreases with that of the cold side.
4. For zero accumulation, the permeability of the cold side of the wall must be many times that of the warm side. The ratio depends on the temperature and vapor pressure differences to which the wall is subjected.
5. A vapor barrier used to prevent accumulation of moisture in a wall should be located on the warm side of the isothermal plane in the wall the temperature of which is at or above the dew point of the air on the warm side of the wall. For extreme conditions it should be placed on the surface of the warm side of the wall.
6. The thermal properties of the wall affect the rate of accumulation of moisture, insofar as the temperature on the inside of the cold side of the wall is influenced.
7. The water vapor permeability of materials used in building construction varies widely. Rosin sheathing papers and fiber insulation boards which have not been "vapor proofed" have very high permeabilities. Heavy asphalt-saturated felts and asphalted kraft papers have very low permeabilities. Aluminum paint when applied in two coats is very effective in adding to the vapor resistance of a material. Masonry materials, including concrete, brick, tile and plaster are permeable to water vapor.
8. Venting the cold side of the wall to the cold air by means of small holes does not appear to be effective in preventing moisture accumulation.
9. The condensation of moisture may take place in uninsulated walls as well as in insulated walls. In the former the moisture will condense at the lower part of the wall, which may be more hazardous than moisture accumulation in an insulated wall, where it is fairly well distributed.

10. The rate of moisture accumulation does not appear to be affected by the hygroscopicity of the insulation.
11. The moisture in hygroscopic fill insulation will be redistributed when placed in a wall and subjected to a temperature difference. The moisture content is decreased near the warm side and increased near the cold side. The extent to which this takes place depends primarily on the temperature difference and the average moisture content of the insulation, which when too high originally, may result in condensed moisture next to the cold wall.
12. A water vapor barrier in the form of two coats of aluminum paint on the inside surface of the wall or asphalt-saturated felts and reinforced kraft papers of relatively low permeability placed on the inside of the warm side reduces the rate of moisture accumulation in walls considerably but not completely.

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